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WOODHULL LECTURE

SOME NEW APPROACHES TO INHERITANCE AND EVOLUTION

By J. F. DANIELLI, Ph.D., D.Sc., F.R.S.
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Weekly Evening Meeting, Friday 5th February, 1960

James Lawrie
Vice-President, in the Chair

THE theory of Mendelian inheritance is very well established. What is not so well established is how much of inheritance is covered by Mendelian theory and how much depends on other processes. The study of inheritance by mating processes is particularly useful in studying inheritance according to Mendelian theory; but it is not such a convenient method for studying non-Mendelian inheritance. Experiments for studying inheritance by non-Mendelian mechanisms are usually rather complicated and difficult to perform, and consequently evidence is accumulating only slowly which can enable us to define the extent of non-Mendelian inheritance.

In 1945 it was already clear that not all inheritance is Mendelian. For example, not all reciprocal crosses are identical, as they should be under Mendelian theory. Secondly, certain particulate bodies cannot be reproduced in the absence of the particulate body concerned, although all the necessary nuclear Mendelian genes may be present. This is the case, for example, with chloroplasts.

A further limitation to the understanding of the extent of Mendelian inheritance is the fact that crosses are only possible between very closely related strains of organisms. Thus the number of situations in which genes or chromosomes are able to function in what would normally be a foreign cytoplasm is very limited.

About 1945 it was decided to try to investigate the limitations of Mendelian theory more radically by nuclear transplantation by micromanipulation. This was attempted both in amoebae and in developing eggs.

Nuclear transfers in amoebae

In principal, the experiment involved is quite simple. Two different strains or species of amoebae are taken. The nucleus is

removed from an animal of one species, and replaced by the nucleus of an animal of another species. These nuclear transfers can be carried out readily by the method devised by Commandon and de Fonbrune.

Amoebae containing the nucleus of one type in the cytoplasm of another will multiply and continue to live as clones for an indefinite period, i.e. as long as appropriate food is supplied. Numerous studies have been made on various characteristics of such amoebae. It has been found that characters which can be considered to be the properties of molecules taken one by one, e.g. the characteristics of the antigens present, are defined entirely by the nuclear genes within the limitations of accuracy of our experiment. On the other hand, numerous other characters, for example the diameter of the cell nucleus, the shape assumed by the cell when moving, resistance to radiation, resistance to streptomycin etc., show some measure of nuclear control and an equally large measure of cytoplasmic control. Thus no characters have so far appeared which are entirely under cytoplasmic control, though some characters have appeared which are entirely under nuclear control. Those characters which involve the functioning of structures made of many macromolecules are as clearly under cytoplasmic control as they are under nuclear control. These characters are the morphological and physiological characters of the organism, whilst the chemical characteristics are under strict nuclear control, so far as we have been able to determine.

Nuclear transfers in amphibians

In the last five years nuclear transfer experiments have been extended to developing amphibian eggs, particularly by Briggs and King, J. A. Moore and Fischberg. In these experiments, a nucleus is taken from a relatively late stage in the development of an embryo and transferred into an egg before cleavage, in such a way that the egg develops under the control of the transferred nucleus. When this is done, it is found that the nucleus from the late stage is frequently able to promote and to control the new egg so that a normal embryo and larva are formed. On the other hand, some of the nuclei taken from relatively late stages of development no longer seem to be completely competent to

make provision for a normal larva, but only to provide for differentiation of some types of organ. It has also been possible to transfer nuclei from one species of amphibian to another. Under such conditions it is frequently the case that although cell and nuclear division can take place involving a nucleus in foreign cytoplasm, normal development cannot occur. An amphibian nucleus which has been present in foreign cytoplasm for some time can be transferred back to its own type of cytoplasm. When this is done, the nucleus is found to be altered by its sojourn in foreign cytoplasm, and to be no longer competent to sustain normal development in its own cytoplasm.

It thus appears to be the case that changes are induced in nuclei by exposure to cytoplasm other than that of the undivided egg. These changes become evident at a relatively late stage in development, and are also rather quickly produced by a period of exposure to foreign cytoplasm. We do not yet know how readily these changes are reversible. Certainly they are not easy to reverse.

Similar changes have been observed in the experiments previously reported with amoebae. When a nucleus is transferred into a foreign amoeba cytoplasm, both the cytoplasm and the nucleus may go through a series of slow and prolonged changes so that both nucleus and cytoplasm eventually become incompatible (or only difficultly compatible) with their original cytoplasm and nucleus. The understanding of the nature of these difficultly reversible changes in nuclei and cytoplasms must inevitably help us considerably in understanding the nature of differentiation.

Other studies of cytoplasmic phenomena in inheritance

P. Michaelis has studied cytoplasmic inheritance in *Epilobium*. There are many diverse species or strains of *Epilobium* in which the reciprocal crosses are fertile, and in which the progeny of these crosses are not identical. By repeated back-crossing to the male parent strain it is possible to obtain plants in which the nuclei, i.e. the nuclear genes, have been entirely derived from the male parent, whilst in principle the cytoplasm has been derived from the female parent. In such plants it is found that a wide variety of physiological and morphological characters are

carried by the cytoplasm including, for example, a measure of control of the rate of nuclear gene mutation. It is not maintained that these crosses are not also controlled by the nucleus. As with amoebae, these crosses appear to be under both nuclear and cytoplasmic control.

Among the bacteria, many cases are also known of infective inheritance, ranging from infection with a single gene to infection with a chromosome. These experiments may be regarded as somewhat analogous to infection with viruses in higher organisms, but whilst in the bacteria many instances are known where the infective gene becomes incorporated in the genotype, there is little evidence of this so far in higher organisms. The lack of this evidence at present is more likely to be due to the difficulty of making appropriate studies than to the absence of such phenomena.

Discussion

The evidence for cytoplasmic inheritance is now so strong that it has become relevant to enquire into the nature of the physical basis for cytoplasmic inheritance. It is generally thought, though by no means proved, that the action of nuclear genes is as follows: each gene contains one or more definite species of deoxypentose nucleic acid (DNA). Each gene also appears to control the synthesis of a particular type of protein. It is perhaps more correct to say each gene makes possible the synthesis of a particular type of protein. The simplest explanation of this relationship would be that a sequence of nucleotides A, B, C etc. in the DNA controls the sequence of amino acids α, β, γ etc. in the protein; i.e. there is a linear correspondence between the sequence of units in the DNA polymer and the sequence of units in the polypeptide polymer. In this scheme the coding is linear or one-dimensional, and the individual signal is a nucleotide.

What can be said at present concerning the physical basis of cytoplasmic inheritance? There is, in fact, no satisfactory evidence. It may be that DNA is involved: an alternative is that RNA (ribose nucleic acid) is responsible. However, some illumination may be obtained by considering the nature of the crosses which bear the imprint of cytoplasmic control. Whilst the characteristics controlled by nuclei are the natures, i.e. the

structures, of individual macromolecules, the characters controlled by the cytoplasm appear to be quite different, i.e. the cytoplasmically controlled characters are those involving the co-operation of large numbers of macromolecules. To put it in another way, cytoplasmic control becomes evident only when we are dealing with structural or morphological phenomena. It thus seems a little unlikely that the cytoplasm is doing the same sort of job as the nucleus. It is more likely that the cytoplasmic control of inheritance is at a different level, and is controlled in a different way.

A further clue to the nature of cytoplasmic inheritance may perhaps be derived from considering the structure of cells as revealed in the electron microscope. The formed structures in the cytoplasm consist of material made only from fibres which may be considered to be based upon a one-dimensional structure, or mainly from membranes, which may be considered to have a two-dimensional structure. It is therefore interesting to consider the possibility that information storage concerned with cytoplasmic inheritance is based upon a two-dimensional, i.e. planar, coding, in which the unit signal consists of an individual macromolecule. Investigations of this are now being considered. Elementary calculations show that if even a small part of the cytoplasm contributes to inheritance in this way, an enormous amount of information can in fact be stored in the cytoplasm.

If the hypothesis that the contribution to inheritance made by the cytoplasm depends upon a two-dimensional coding of this type, some interesting consequences follow from the point of view of evolution. If a significant change is to occur in a structure, it must involve simultaneous complementary changes in two adjacent molecules. Thus, whereas Mendelian mutations depend on the mutation of Mendelian genes taken one by one, since only one molecular species is involved, corresponding changes in cytoplasmic inheritance must involve at least two macromolecules and so depend upon the rate of mutation of Mendelian genes taken two by two. Or at least cannot occur more frequently than the rate of mutation of Mendelian genes taken two by two. The rate of mutation of genes taken two by two is so much less than the rate of the same genes taken one by one that it would inevitably follow that the rate of evolution is controlled by the

rate of mutation of genes taken two by two, i.e. contemplation of evolution as a consequence of simple mutation of Mendelian genes may be quite misleading.

EXHIBITS IN THE LIBRARY

A display of apparatus for micromanipulation of amoebae, and for transferring a nucleus from one cell to another; living amoebae; photographs of different types of amoeba; arranged by *Dr. S. E. Hawkins, Mr. R. Cole and Miss A. Muggleton, King's College, London.*

INFRA-RED RADIATION

By R. V. JONES, C.B., C.B.E., M.A., D.Phil.
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Weekly Evening Meeting, Friday 18th March, 1960

H. Heywood, D.Sc., Ph.D.
Vice-President, in the Chair

ONE of the most famous experiments in Optics was Newton's use of a prism to disperse white light into the visible spectrum. It was soon noticed that heat seemed to be carried along with the light in the spectrum, and it was assumed that the amount of heat carried was proportional to the visual intensity of the light. In 1800, however, Sir William Herschel wrote that "It is sometimes of great use in Natural Philosophy to doubt of things that are commonly taken for granted. . .", and the particular thing of which he doubted was this proportionality between the heating effect and the intensity of light as judged by the eye. He described (Herschel 1800) how he had placed a thermometer in various parts of the spectrum produced by a prism, and how he had found that the thermometer had actually indicated a greater heating effect in the dark region beyond the red end of the spectrum than existed anywhere within the range of colours that he could see. He recognized that he had discovered invisible rays similar in many of their properties to those of visible light, but less refrangible even than the rays in the deepest red of the spectrum.

Now what is the relation between these "infra-red" rays, and the visible light to which our eyes are accustomed? We may expect them to be very similar, from the fact that they are made manifest by the same prism that refracts and disperses white light into its constituents. Just as we know that red light has a longer wavelength than blue light, so we may expect infra-red radiation to have a longer wavelength even than red light; in fact the range of infra-red wavelengths extends from about 0.7 micron (10000 microns = 1 centimetre) to about a millimetre—waves even longer than this are emitted to some extent by all bodies, but they are more specifically generated by radio techniques. We know that visible light is emitted by bodies that are sufficiently hot; a body at 500°C emits a little red light, then

at 1,000°C there is more red and a little of the other colours, giving an overall appearance of orange. At about 10,000°C, there is much more of all colours, and particularly of blue and violet, so that the surface of a very hot star appears bluish white. Generalizing, we may say that all bodies emit radiation at all temperatures, that any one body emits more radiation at a higher temperature, and that the proportion of short-wave radiation goes up as the temperature is increased. We may therefore expect that at low temperatures, say below 500°C, almost all the emitted radiation is invisible, and is in the infra-red. This turns out to be so, and a detailed experimental study with blackened surfaces shows that at any temperature there is a maximum amount of radiation emitted at a wavelength which, when measured in microns, is given approximately by dividing 2900 by the absolute temperature of the emitting surface. Thus, at room temperature, about 290° Absolute, the maximum radiation occurs at a wavelength of 10 microns. This is well into the infra-red, at a wavelength about twenty times that of green light.

In passing, we may note that the distribution of energy with wavelength in the radiation from a hot body was the subject of very careful measurements by Rubens (1900) and his collaborators towards the end of the nineteenth century. Their curves could not be explained by classical theories of radiation, and the discrepancies led Planck to postulate that light (and infra-red radiation) was emitted in tiny packets. Planck (1901) showed that this hypothesis could be made to reconcile the discrepancies; it was the beginning of the quantum theory, which was easily the most outstanding contribution to Natural Philosophy to have originated in infra-red studies.

Before we look in more detail at the properties of infra-red radiation, let us consider the means by which it can be detected. The first main class of detector is known as the "thermal" type, since in principle it uses the same basic heating effect that Herschel detected with his mercury thermometer. The radiation is made to fall on a small receiving area, usually blackened, and the temperature rise in this receiver is measured by a minute thermometric device. The exact nature of this device varies with the instrument; in the thermopile, for example, tiny thermocouple wires are connected to the receiver, and the electro-

motive force generated at the junction is measured by the current that it produces. In the bolometer, the electrical resistance of the receiver foil increases as it is heated by the radiation, and the increase in resistance may be taken as a measure of the strength of the incident radiation. In the Golay cell, the receiver is surrounded by gas in a small capsule, and the rise in temperature causes the gas pressure to increase; this increase is measured

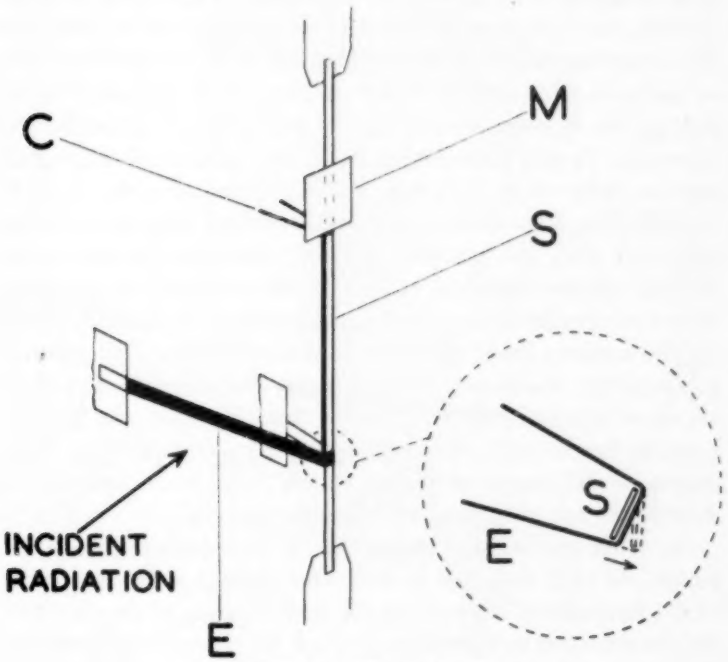


FIG. 1. Principle of Expansion Device.

by the distortion produced in a membrane forming one wall of the capsule.

These devices may be made impressively sensitive, but we are immediately set wondering whether there is any limit to the sensitivity that can be achieved. It turns out that there is such a limit, owing to the discontinuous structure of the natural world as we observe it; the limit arises in the following way. We have seen that all bodies emit infra-red (or more generally electromagnetic) radiation to some extent. If we imagine our detector

to be placed inside an enclosure, all at the same temperature, the detector will receive radiation emitted by the inner walls of the enclosure, but it will at the same time emit radiation itself, and this radiation will be picked up by the walls of the enclosure. There will thus be a continuous exchange of radiation between the detector and the enclosure, equal amounts of energy on the average flowing in both directions. But when we inspect this flow of energy more closely, we find that it is travelling in small packets, the "photons" of the quantum theory. Now, although there may be a large number of photons in quite a small amount of radiation, this number is not infinite; let us suppose that on average the detector is emitting and receiving a million photons a second. In one particular second, the total number emitted may be rather more than this, say one thousand more, while in the following second the total number emitted may be one thousand less than the nominal million; these fluctuations occur because of the statistical nature of the emission phenomena. There are similar fluctuations in the numbers of photons falling on the receiver from the walls of the enclosure. The photons carry energy, and thus in any one second there may be a random excess or deficiency of energy in the detector due to the fluctuations in the balance of incoming and outgoing photons. This excess or deficiency of energy shows itself in an increase or decrease in the temperature of the detector.

So, if we look closely enough at the temperature of our detector, we shall find that it fluctuates slightly. The magnitude of the fluctuations depends on the heat capacity of the detector, and on the mean temperature at which the detector is operating. In practice, the fluctuations can be quite appreciable. For a typical receiving surface of about 1 mm^2 in area and about 0.1 micron thick, they are as large as one millionth of 1°C. This means that the receiver can only be made to detect infra-red radiation if this radiation causes a temperature rise large enough to be clearly distinguishable from the random rise and fall in temperature due to the natural fluctuations. The actual minimum amount of radiation that can be detected by any one receiver depends partly on its area and on its temperature, and partly on the time which we are prepared to devote to the measurement. The longer time we have available, the more precisely can we

average out the effect of the natural fluctuations, and therefore the more easily can we recognize a temperature change due to the infra-red radiation that we are trying to observe. The limit can be calculated quite precisely: for a receiver of 1 mm^2 in area, with an observing time of 1 second, the incident rate of energy

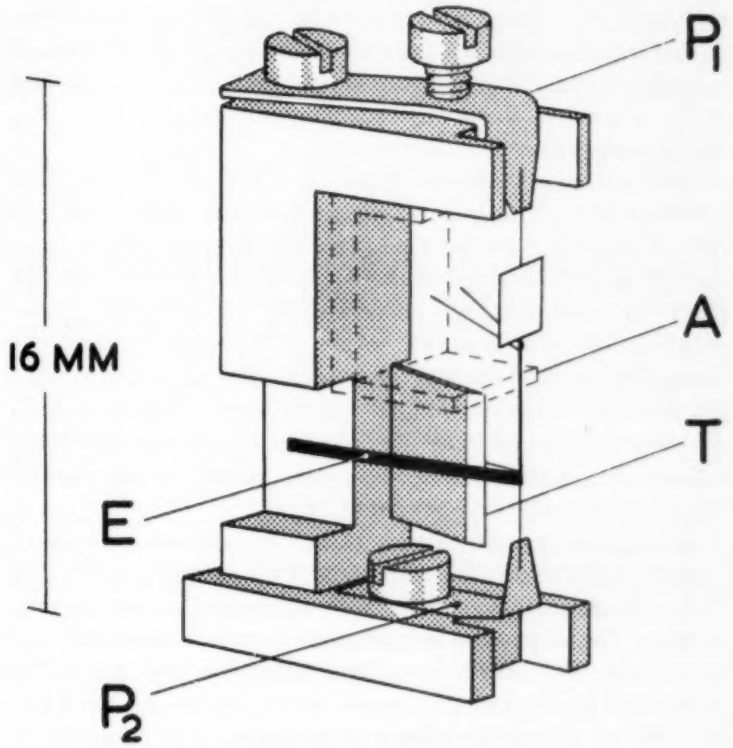


FIG. 2. Linear Expansion Infra-Red Detector.

that would cause a temperature rise equal to the root mean square of fluctuations is about 5×10^{-12} watt.

So far, in practice, we have not made any instrument quite as good as this natural limit would allow. One of the instruments that has come nearest to it is a detector based on the very simple phenomenon of linear thermal expansion (Jones 1959). Supposing that we have a strip of foil 5 mm long and 0.2 mm wide, the root mean square value of the temperature fluctuations is, as we

have seen, about 10^{-6}°C. If we look very carefully at the length of the strip, we shall find that this length is fluctuating, as the temperature rises and falls, and, since a typical linear expansion coefficient is about 10^{-5} per °C, the fluctuations in length of the strip are about 5×10^{-12}cm. This is about the diameter of a typical atomic nucleus, and at first sight it does not appear easy to observe. However, by arranging for the strip to be fastened so that any expansion or contraction can be made to turn a small mirror, an optical lever can be made to detect quite small changes in the position of the mirror; it then turns out that these very small changes in length can be detected.

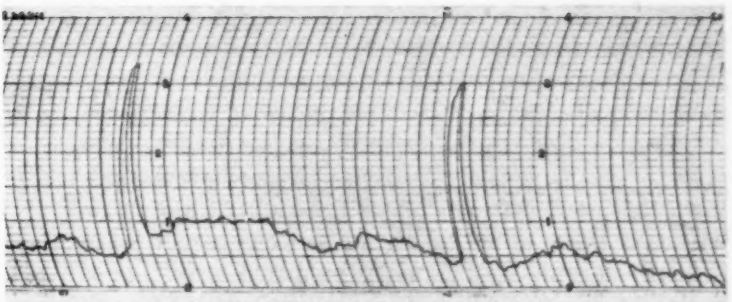
The detecting device is shown in Figure 1. The incident radiation falls on the expansion strip E, which acts as a pair of reins pulled tight around a taut suspension strip S of the type used in galvanometers. The radiation causes expansion of that part of E on which it falls, and this expansion allows the corresponding edge of S to move forward. The part of S crossed by E thus rotates, and the rotation is transmitted to a mirror M, a few millimetres away from E so that the light falling on M from the associated optical lever does not heat E. The part of S lying between E and M is stiffened by copper plating, so that the full rotation at E is also experienced at M.

As regards the dimensions of the system as constructed (Figure 2), the expansion strip is about 5 mm long x 0.1 micron thick; the material is constantan, to minimize heat loss by conduction. The suspension strip is about 50 micron in breadth and 9 mm long. The mirror is as light as possible, and is made of aluminized glass 1.5 mm x 1.5 mm in area, and 60 micron thick. In order to reduce the effects of vibration, it is necessary to counterpoise the mirror in order to bring the centre of mass into the axis of rotation. This is achieved by a "hairpin" of manganim wire, about 4 mm long and 25 micron in diameter. The counterpoising has to be better than 1 microgram at 1 mm off axis.

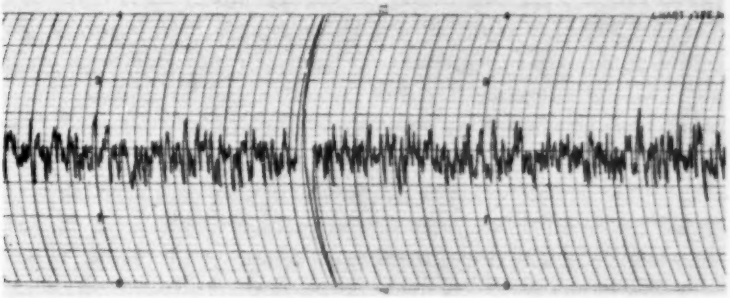
This device is placed in a vacuum, and the mirror is observed by means of the optical lever system; some of the records are shown in Plate I.

The "noise equivalent signal" for the device corresponds to about 10^{-11} watt for an observation time of about 1 second, which is within a factor of two of the "ideal" sensitivity. In everyday

A



B



Expansion device records. (A) Record showing zero drift, with superimposed deflexions due to reception of radiation at rate of 1.7×10^{-9} watt. One vertical division represents an expansion of 5×10^{-11}cm, or a temperature rise of about 5×10^{-5}°C. On the scale of original record, an expansion of 1 micron would give a deflexion of 5 km; the amplifier was operating at about one-fortieth maximum gain. (B) Record with capacitances inserted to eliminate drift, and amplification increased. Positive and negative deflexions due to switching on and off incident radiation of magnitude 4×10^{-10} watt. One vertical division corresponds to velocity of perhaps 30 microns per annum.

On both records 1 horizontal division = 2 seconds.

PLATE I

terms, the achieved sensitivity is such that the heat from a candle a hundred yards away, falling directly on the 5 mm strip in the detector, would cause just enough expansion to be detectable. If we were to place a detector at the focus of a mirror 200 inches in diameter, the mirror would collect enough heat to be able to detect a candle at 400 miles range.

Earlier in the Discourse, I mentioned that there were two main classes of infra-red detector. So far, we have only dealt with the "thermal" type, but there is another type which has become very important in the last twenty years. This type makes use of the properties of semiconductors. Whereas a metal contains many free electrons, nearly all the electrons in a semiconductor are bound to individual atoms. Some of these bound electrons can, however, be agitated sufficiently to be shaken away from the individual atoms, and they are then free to move through the material. One way in which this agitation can be achieved is merely by virtue of the thermal movements of the atoms themselves, due to the temperature of the material; the electrical conductivity therefore increases as more electrons become free as the material warms up. Another way of freeing the electrons is by means of radiation coming in from outside the material, in the form of photons; if an individual photon has sufficient energy it may give this up to an electron, which is then free to move. The energy required in the photon, of course, depends on how tightly the electron is bound to its original position in the crystal. Studies of the nature of semiconductors have pointed the way for the development of materials in which the electrons are only very loosely bound to particular positions in the crystal, and thus can be removed by photons of very low energy, corresponding to radiation of comparatively long wavelength. Some of the semiconducting materials work best when they are made as pure as possible, but it has been proved that sensitivity to even longer wavelengths can be achieved by taking pure materials such as germanium, and incorporating in them impurities such as gold, since electrons are bound even more gently to the gold atoms than they are in the bulk germanium. In general, these substances can detect long-wave infra-red radiation effectively only when they are cooled to low temperatures, because otherwise the agitation due to the temperature of the material would

in any event lead to most of the vital electrons being shaken free, and thus obscuring the effects due to any electrons released by photons coming in from outside. Once electrons have been released by incoming infra-red radiation they can be detected by establishing an electrical potential difference across the material, when a current will flow due to the motion of the electrons. This current can then be amplified and made to operate a suitable indicating device. The sensitivities achieved by these photoconductive cells, as they are called, are very impressive, and they form the basis of many recent detectors.

For the purpose of demonstrating some of the properties of infra-red radiation in this Discourse, we have constructed an infra-red detector at Aberdeen which consists in principle of two small thermo-elements on which the image of a distant source is focused by a mirror about 10 cm in diameter. The mirror is made to vibrate in such a way that the image of the source falls first on one thermo-element and then on the other, and these elements then generate a small alternating current which is amplified and indicated by an ammeter whose pointer can be seen by projection on the screen. (The system has the merit, for demonstrations in a heated lecture room, of being sensitive to sources of small size, and of substantially ignoring any large area, either hot or cold, of uniform temperature). A difference in temperature of 0.01°C between the source and its background —the source being about 1 ft. high by 1 in. wide at a distance of 60 ft.—can be detected by this instrument, which has a response time of rather less than 1 second. This is not, incidentally, the maximum sensitivity that can be achieved. Using larger mirrors and better detectors, a temperature difference of 0.001°C or 0.0001°C can be detected. The present sensitivity is, however, ample for our purposes, the first of which is to demonstrate simply the detection of infra-red radiation at a distance, the source being a human finger at a distance of about 20 ft. If instead of a finger, which is warmer than its surroundings, we substititute a piece of ice, we see that the indicator moves in the opposite direction. This is because the detector is now losing heat across the distance of the lecture room to the piece of ice.

It is easy to demonstrate that infra-red radiation obeys the same laws of reflection as those appertaining to visible light. For

this purpose a soldering iron has been mounted in the roof of the lecture room, and a surface-aluminized mirror has been placed on the floor, some distance away from the detector. When the detector is sighted on the mirror, it "sees" the soldering iron in the roof, because the mirror is arranged at a suitable angle. A small optical projector has been mounted along with the infra-red detector, so that the light from the projector points exactly in the direction in which the detector is "looking". It can be seen that the light from the projector is striking the mirror, and is reflected to the roof where it illuminates the soldering iron. This effect shows that the path pursued by the visible light on reflection is the same as that pursued by the infra-red radiation.

It is also possible to demonstrate the transmission and refraction of infra-red radiation by suitable materials. In the demonstration, we have a crystal of lead fluoride about 4 inches in diameter by 4 inches thick, which has been grown at Aberdeen. We have in fact grown crystals of many materials, and it is interesting to remark that I was first led into growing crystals for infra-red purposes by a paper published by Sir James Dewar (1920) from the Royal Institution. He had noted that sheets of silver chloride transmitted thermal radiation, and I happened to read this at a time when I was looking for suitable materials for making "windows" for infra-red detectors before World War II. I therefore started to grow crystals of silver chloride, and after the war we extended the technique to a good many more materials. One of these is lead fluoride, and by placing this crystal in front of the detector, it can be seen that the detector continues to function, showing that the infra-red radiation must be getting through the crystal. By contrast, quite a thin sheet of glass placed in front of the detector cuts off the infra-red radiation, and so even quite a strong source, such as a human hand, cannot be "seen" by the detector through the glass. We have also a prism of lithium fluoride, which can be placed in front of the detector, and it can easily be demonstrated that the line of sight of the detector is now completely changed, because of the bending of the radiation which is produced by the prism. One can also show that infra-red radiation is dispersed by a diffraction grating.

Another demonstration concerns the absorption of infra-red radiation by gases. Much work was done on this subject in the

Royal Institution about a hundred years ago by John Tyndall. As can be shown with the present detector, the absorption is not very great, and we must admire Tyndall's experimental skill in showing this absorption with the much less refined apparatus available in his time. A tube about 5 inches in diameter by about 1 foot long can be placed in front of the detector, and the tube can be filled with coal gas. By comparing the deflection of the indicator produced from a distant source, before and after the tube has been filled with coal gas, we can see that the coal gas must be absorbing a small fraction of the radiation going through it. This absorption is very largely due to the methane in the coal gas, which we shall examine in more detail a little later.

It will be clear from the demonstrations that the infra-red detector has possibilities as a device for seeking sources different in temperature from their background; a final demonstration with this detector is to take a black curtain at some distance from the detector, and to touch this curtain momentarily with one's hand. The detector can then be made to scan the curtain and to find which point it is that has been touched, even one minute later.

Returning to the nature of absorption by gases, the phenomenon arises in the following way. If we consider a methane molecule, which consists of a carbon atom, with four hydrogen atoms bound to it, these latter atoms forming a tetrahedron with the carbon atom at its centre of gravity, the bonds which hold the hydrogen atoms to the carbon atom have some of the properties of springs, and the effect of this is that if the hydrogen atoms are drawn aside they will vibrate relative to the carbon atom. Since the hydrogen atoms have a definite mass, this in conjunction with the springing of the bonds constitutes an oscillating system with a definite frequency. Because of the strength of the spring and the lightness of the atom, the frequency is high, in fact about ninety million million cycles per second. This frequency corresponds to that of infra-red radiation of wavelength of about 3.3 micron, and it therefore turns out that the methane molecule can resonate to infra-red radiation of this wavelength and absorb it. Vibration, however, is not the only motion to which the molecule is subjected. It forms part of a gas consisting of enormous numbers of other molecules, and

is in very frequent collision; the effect of the collisions, which we can visualize by thinking of the tiny tetrahedra colliding with one another, is that not only the tetrahedra rebound from one another but in the process they develop a certain amount of spin. It turns out from quantum considerations that the spin has to take a definite series of values. Now the effect of the spin on the individual molecule is to stretch slightly the bonds joining the hydrogen atoms to the carbon centre, and thus to alter somewhat

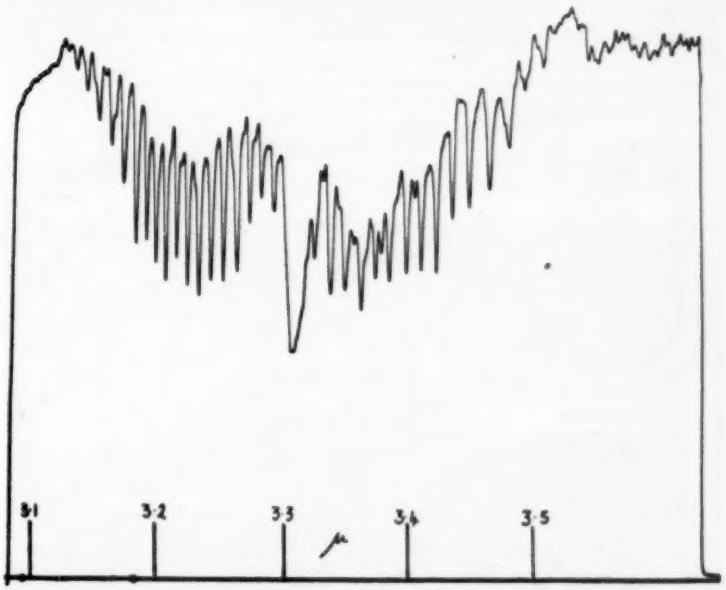


FIG. 3. Record showing vibration-rotation structure of methane absorption band at about 3.3 microns wavelength, made with special Mervyn Instruments demonstration recorder during the Discourse. Original record measured 36″ x 30″.

the frequency to which the molecule will resonate. The result on the absorption spectrum is rather like that of superimposing a series of audio-frequencies on the carrier wave from a broadcast transmitter, which builds up a series of "sidebands". This effect, the family of sidebands due to rotation superimposed on the main resonance frequency of the methane molecule, can be demonstrated by plotting its absorption spectrum with an infra-red spectrometer. The Mervyn Instrument Company has kindly provided a demonstration, which will enable us to see the spectrum

drawn out on a recorder, which may well be the largest of its kind ever made, specially constructed for this Discourse. The fundamental vibration and its sidebands can clearly be seen (Figure 3).

Infra-red spectroscopy has two principal values in chemistry. The first is that it enables the vibrations of particular groups of atoms to be studied, and this provides us with information from which we can deduce the nature of the structure binding the atoms together, and the strength of the bonds. It has thus made important contributions, particularly to organic chemistry. The

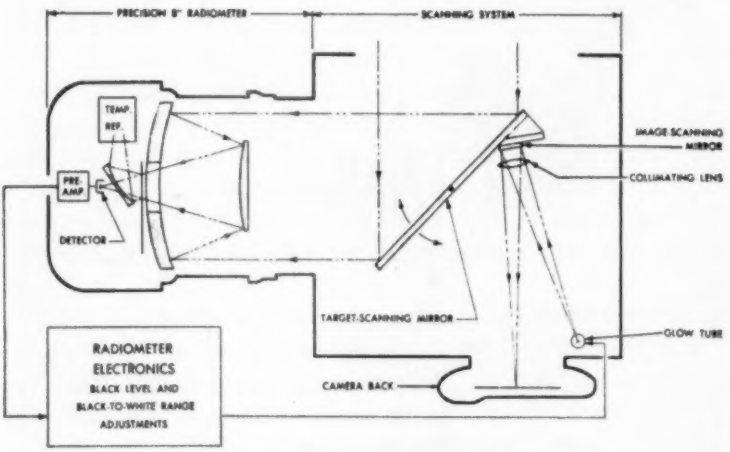
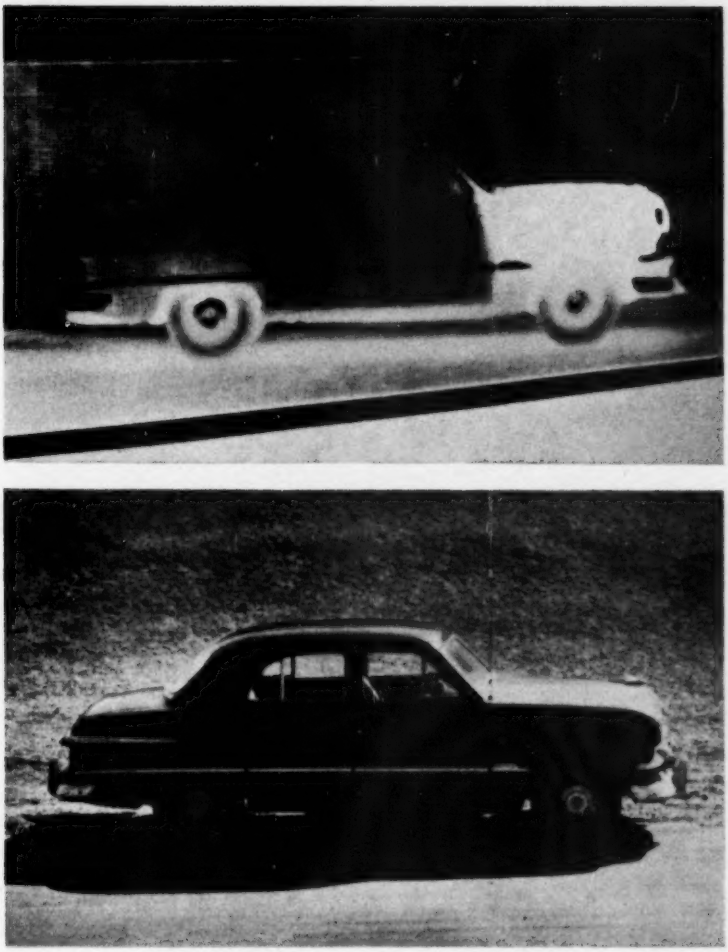


FIG. 4. Schematic diagram of Barnes Engineering Company's Infra-Red Camera.

second application is that of a finger-printing device. Once the infra-red spectrum of a particular group of atoms is known, it can be used as a means of identifying the existence of this group in some unknown compound, or for detecting the appearance of some particular compound in, for example, the products of a chemical process. Infra-red spectrometers can thus be set to monitor industrial chemical processes, and to watch for the appearance of undesired products. Infra-red spectroscopy has many other applications, but it is these particular ones that have led to its widespread use in pure and applied chemistry.

An interesting possibility is the production of infra-red pic-



Infra-Red photograph (Thermograph) taken by Barnes Camera (above) compared with normal photograph (below). *Reproduced by permission from Drs. R. W. Astheimer and E. M. Wormser.*

PLATE II

tures. There are many ways of doing this; in principle, they consist of constructing a picture in which the points of greatest infra-red intensity are indicated by points of greatest visual brightness. Some of these devices work on principles similar to those employed in television cameras. The one which I believe to produce the best pictures is that developed by the Barnes Engineering Company in America, and I am particularly indebted to Dr. Astheimer and Dr. Wormser for permission to show you some of their pictures. Their instrument (Figure 4) consists of a small thermistor bolometer (in which the incident infra-red radiation causes a change of electrical resistance), mounted at the focus of a concave mirror. In front of this mirror is a large plane mirror which is moved in such a way as to scan the field of view on a raster pattern rather like that you may see on the screen of any television set. The movement of this plane mirror enables the detector to "look" at a field of view in a point-by-point fashion, and if at any particular point there is a source of infra-red radiation, the detector is made to light a small lamp whose brightness is made proportional to the intensity of the incoming radiation. An image of this lamp, reflected off the rear of the plane scanning mirror, is made to fall on a photographic film, and a visual picture is thus built up point by point on the film. Drs. Astheimer and Wormser (1959) have produced many impressive pictures (several were shown in the Discourse); one is of a motor car as seen by infra-red radiation, shown for comparison with a normal photograph of the same car produced by ordinary light (Plate II). Not only can the increased infra-red radiation from the bonnet (due to the heat of the engine) be seen, but the photographs also show clearly the lack of radiation from the bright metallic surfaces such as those of the bumpers and the ornamental line along the side of the car. This is because the metal surfaces, which are good reflectors, are poor emitters of radiation; so that, even though these surfaces are at the same temperature as the sides of the car, they emit less radiation and thus show up as dark areas in the infra-red picture.

Another technique by which infra-red pictures can be produced is to focus an infra-red image on to a thin film of oil, causing some of the oil to evaporate where the infra-red radiation is strongest. This alters the thickness of the oil film, and this

change in thickness can be revealed by optical means. I am indebted to Dr. D. Z. Robinson of the American Office of Naval Research for allowing me to show some pictures that he produced by this process while he was on the staff of Baird Associates in America.

One development in the field of infra-red pictures has been the possibility of mounting a suitable device in an aircraft in order to produce infra-red pictures of the area below. It is thus possible to fly at night, and produce pictures which look rather like ordinary aerial reconnaissance photographs with sheets of water showing up as dark, and warmer areas, such as houses and towns, showing up as bright. I am indebted to the Royal Radar Establishment for allowing me to show a picture that has been obtained by this technique.

The idea of using infra-red detection for military purposes seems to have started in World War I; Lord Cherwell once told me that he had proposed its employment in 1916. According to Dr. H. Gaertner, the Germans detected British torpedo boats off Ostend at a range of about 10 km by the radiation from their funnels. In America, Hoffmann developed a detector in 1918 for detecting men and other objects at a higher temperature than their background, in the dark, by their thermal radiation; he also developed an aircraft detector. The Royal Navy had a short range signalling system before World War II which depended for its security on the invisibility of infra-red radiation.

I myself spent much of 1935, 1936, and 1937 on developing an infra-red detector of aircraft for the Air Ministry, using thermopiles to pick up the heat radiated by the aircraft. The apparatus was quite small, and very similar to the one demonstrated in this Discourse. It would indicate whether the target was right or left of (and above or below) the line of sight, and it would "see' a single-engined 500 h.p. aircraft at two miles or more. It could even "see" an aircraft at 100 m.p.h. with its engine switched off, because the aircraft became about 1° hotter than the background on account of its motion through the air. We actually had the equipment flying experimentally in 1937 in an effort to provide our night fighters with some means of detecting raiding bombers, but the work was stopped in 1938 because of the greater promise of radar.

Royal Air Force 'Hunter' aircraft carrying two 'Firestreak' missiles. *Reproduced by permission from the Ministry of Aviation and the de Havilland Company.*

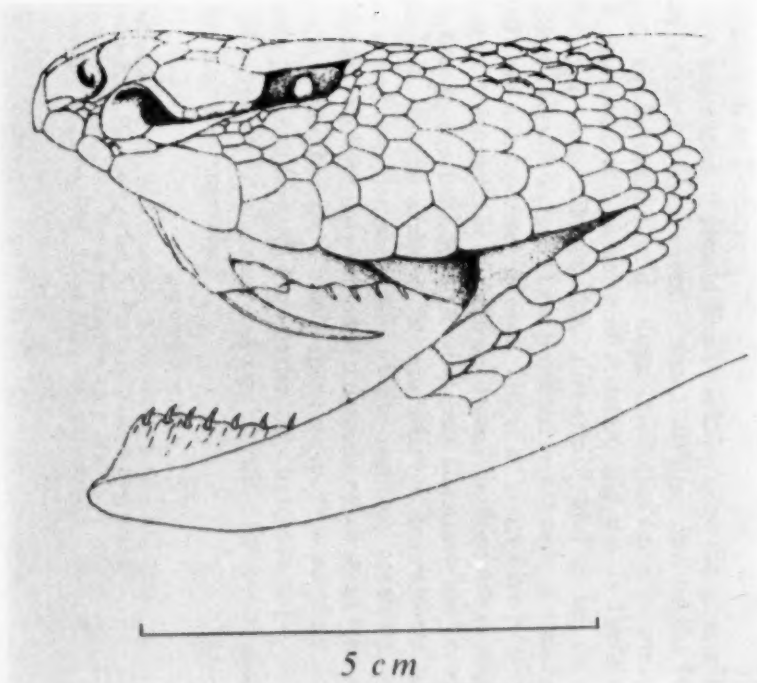
PLATE III

The Germans were experimenting with infra-red detection at about the same time. From the records, it appears that we were ahead in 1937, but the Germans produced lead sulphide photoconductive detectors and persevered with the system after we had dropped it for radar. They set up infra-red equipment near Gibraltar in 1942, in an attempt to pick up the heat from the convoys steaming through the Straits, and they produced an infra-red scanning detector for some of their night fighters towards the end of the war. As far as I know, its tactical contribution was small, although its technical achievement was most impressive. At that stage, I was not concerned with the development of detecting systems, since I spent the war in Intelligence, but it was of course with much interest that I discovered that the Germans were proceeding with infra-red detection well beyond anything that we had done. As a result of the German developments, both ourselves and the Americans switched considerable effort into the infra-red field with impressive results. Much of the credit for the development of the new types of photoconductive cell must go to the Royal Radar Establishment at Malvern, and this development has made possible the devising of high speed detectors capable of homing missiles on to even supersonic aircraft. Simultaneously with the improvement of sensitivity of the detector, there has been a great increase in the power of aircraft engines, and in aerodynamic heating, and so the infra-red homing missile is now a standard part of the defensive equipment of major military powers. The first American missile was called "Sidewinder", probably because the Sidewinder is a small rattlesnake which happens to be one of the hazards of the experimental station where the missile was developed. We shall see later that this is an interesting coincidence. Our own missile is the "Firestreak" (Plate III shows two missiles mounted on a "Hunter" aircraft) and by courtesy of the Ministry of Aviation and the de Havilland Company I am able to show a model and a film demonstrating its homing ability.

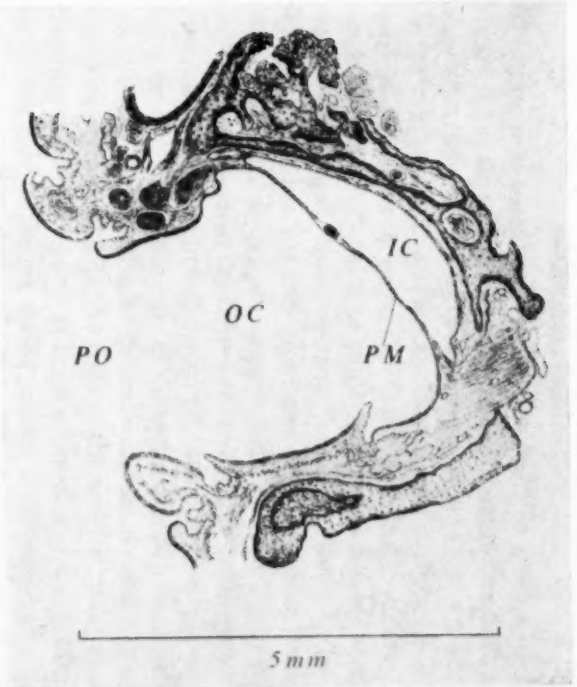
As regards the range possible with military infra-red devices, this depends primarily on four quantities: the power radiated by the target, the absorption in the atmosphere, the size of the collecting mirror, and the sensitivity of the detector. In addition, the fluctuations in radiation from the background may limit the

usefulness of the system, since the signal from the target needs to be well above these fluctuations if it is to be positively identified. The worst targets are sources such as tanks in close country, or aircraft against the sun (which is of course an emitter of infra-red radiation on a blinding scale); in such cases a range of only a mile or two may be all that is practicable. The best sources are aircraft and rockets at high altitudes where the atmospheric absorption is small and the background uniform. Moreover, the power radiated from the target, either directly from the plume of the jet, or from the aerodynamic heating of the leading surfaces is very large. In these circumstances, we may expect ranges of a thousand miles or more.

When we have developed a detector or navigating device for military purposes, we frequently find that a device using similar principles has already been evolved in Nature. The acoustic radar used by bats and the polarization compass of the bees are well known. It turns out with infra-red, too, that its use as a means of detection has been anticipated by several varieties of snake. Among these, the class of snakes known as "Pit-Vipers" show natural infra-red detection at its greatest development. The "Pit-Vipers" are a large family, which includes all the rattlesnakes, and it thus appears that the American "Sidewinder" missile was unwittingly named with insecure propriety. The detection organs are two pits, situated one on either side of the head of the snake, between the nostril and the eye (Plate IVA). Their function was first positively identified by Noble and Schmidt in 1937, by experiments which involved blind-folding the snakes, and observing their ability to strike at warm sources. The employment of two detectors, one on either side of the head, gives the snakes the ability to estimate direction, and they can therefore strike at a warm or cold source in the dark at a range of a foot or so. The structure of the pit organ is shown in Plate IVB. The means of detection appears to be a membrane stretched across each pit near its bottom; this pit is about one thousandth of an inch thick, and is served by an elaborate nervous system. In 1952 Bullock and Cowles in California succeeded in connecting an electrode to a branch of the trigeminal nerve, which is one of the three nerves that serves the membrane, and they detected the changes in the nerve impulses arising when the



A



B

(A) Head of Lachesis Mutus (Bushmaster) showing pit. (B) Pit Organ of Crotalis Terrificus (South American rattlesnake). PO Pit opening, OC Outer Cavity, PM Pit Membrane, IC Inner Cavity, *after* G. S. West, 1900.

PLATE IV

membrane was stimulated by the proximity of a warm or cold source. They showed that the heat from a human hand one foot away from the snake would cause a response, and they found that the membrane could also detect cold sources. Since the pit organ bears some resemblance to the Golay pneumatic detector, it would be tempting to assume that the pit organ is some form of natural Golay cell. However, this is most unlikely to be so, since the impulses are still developed when the membrane is punctured; this would not happen with a Golay detector. It therefore appears that the means of detection is by the temperature rise in the membrane caused by radiation from the object being detected. The structure of the organ can then be rationally interpreted. The membrane has to be free from contact (except round its periphery) with the body of the snake in order that its response will be rapid and as large as possible. Its situation towards the base of the pit would protect it to some extent from undesired disturbances, both thermal and mechanical. So, once again, one of the latest military weapons has been long ago anticipated by Nature.

In conclusion, I should like to acknowledge the great assistance that I have received in this Discourse. Besides the help provided by the staff of the Royal Institution and my own staff at Aberdeen, the Ministry of Aviation and the de Havilland Company have allowed the "Firestreak" film to be shown. Messrs. Grubb Parsons have provided an example of a modern infra-red spectrometer, Messrs. Hilger & Watts have provided a spare thermopile in case the one from Aberdeen was damaged in transit, the Infra-Red-Development Company has brought an infra-red gas-analyser, Messrs. Mervyn Instruments have produced the demonstration of the methane spectrum, and Messrs. Mullard have provided a demonstration of an infra-red photophone. Messrs. Unicam Instruments have provided illustrations for slides; and I am particularly indebted to Dr. D. Z. Robinson, Dr. Astheimer, and Dr. Wormser for permission to use their thermographs.

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A SURVEY OF THE CONFLICT BETWEEN EVOLUTIONARY THEORY AND CHRISTIAN BELIEF

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Weekly Evening Meeting, Wednesday 18th May, 1960

E. R. Davies, O.B.E., B.Sc., F.Inst.P.
Vice-President, in the Chair

WE stand almost exactly at the centenary of the discussion on evolution between Samuel Wilberforce, Bishop of Oxford, and T. H. Huxley, held during the meeting of the British Association for the Advancement of Science at Oxford in June 1860. At the present day, most people seem to think that the problems which then aroused such excited controversy have been settled, but more searching enquiry suggests that Christians and agnostics take this view for different, and incompatible, reasons. Should we accept T. H. Huxley's statement, made a quarter of a century after the initial debate, that "the doctrine of evolution is neither Anti-Theistic nor Theistic. It simply has no more to do with Theism than the first book of Euclid has"?

In attempting to clarify the complex issues involved, I should add that, if we now see more clearly than our great-grandfathers, it is due to their efforts to reach the truth and not to our own superiority. Also, behind the conflict over evolution was a deeper division, scientists claiming that they fought for full freedom of enquiry, and theologians for the preservation of man's spiritual values.

In 1860, the most serious difficulty was the contradiction between the theory of evolution and the account of creation in Genesis, but hardly any Christians are troubled by this today, since it is widely accepted that the first two chapters of Genesis are, and were intended to be, allegory, and that their spiritual message could not otherwise have been conveyed and is really unaffected by later scientific discoveries.

When animal evolution came to be accepted, the attack was turned against natural selection. On this theory, hereditary or innate changes are constantly occurring in animals, their directions being random, *i.e.* non-adaptive, and because there is a

tremendous annual mortality, on balance those hereditary traits which result in more surviving offspring are those which persist and spread in the population, while less well adapted innate characters are eliminated.

The critics claimed that so random a method was totally inadequate to have produced animal evolution, and after the Lamarckian view had been discredited that characters acquired during the life of the parents could be passed to their offspring, they postulated instead an external Life Force, Creative Evolution, or Holistic Urge, directing evolution along particular ways, culminating in man. Such views were first advanced chiefly by agnostics, such as Samuel Butler, Bergson and Bernard Shaw, but in recent times also by various Christians, including Canon Raven and, in modified form, by Teilhard de Chardin.

The critics, nowadays admitting that natural selection may explain minor differences, still claim that it cannot produce big evolutionary novelties, and in particular that it cannot produce the complex, interlocking and synchronous changes, functional at every stage, that are needed for such elaborate organs as a bird's wing or the human eye. The postulated synchrony in such adaptations may not, however, be needed. For instance, de Beer showed that the wing of the bird-reptile Archaeopteryx, though fully feathered, lacked muscles to flap it; it was evidently used for gliding. Hence part of the elaborate mechanism of bird-flight was fully evolved before another part was started, and such "mosaic evolution" has probably been widespread. Again, in different types of animals alive today, one can find many intermediate conditions between a mere light-sensitive area in the skin and the elaborate focussing eye of a man or octopus, all of these stages being functional and well adapted for the animals possessing them.

It was also argued that elaborate adaptations could never have been produced "by chance", but this is a misconception, for selection is the reverse of chance. Moreover the alternative to natural selection, a Life Force or Holistic Urge, solves nothing, it is merely a name for what is not understood, and introduces an unverifiable pseudo-mystical entity into the domain of science, where such concepts are inappropriate. Anyway it implies that the hereditary changes, the mutations, are directive, whereas in

fact they are random, and it is their subsequent selection that determines the directions (not direction) of evolution. It is true that natural selection has so far been proven only for small changes, but it is a reasonable inference that it has operated to produce the big evolutionary changes of the past, very gradually, and functionally at every stage.

A century ago, the one popular argument for the existence of God was Paley's, that animal adaptations are so marvellous that they must have had a Designer. Darwin showed, instead, that they came about by natural means, not as already explained by chance, but by natural causes or laws. Theologians today reject Paley's argument based on particular adaptations. There is, of course, a much stronger philosophical argument from design, that a universe governed by natural causes or laws must have been divinely instituted, but acceptance of the biological theory of evolution makes this argument neither weaker nor stronger than before.

Darwin's views were also feared as implying a strictly mechanistic or deterministic view of the origin of living things, including man. But all that has been demonstrated is a particular historical sequence of animals, within which only some of the many possibilities have been realised. The relationship of such a sequence to determinism, and the bearings of determinism on Christian belief, are extremely complex metaphysical questions on which, once again, particular theories of biology can throw no special light. Hence Christians were wrong to attack Darwin's theory on the grounds that it meant that evolution was "blind", since so far as the biological evidence is concerned, they are as free to hold that the natural means of evolution are a divine creation as atheists are to deny this.

Natural selection was also rejected because it involves a huge annual death-rate, and to humanists like Bernard Shaw it seemed inconceivable that such terrible means could have led to man, with his sense of beauty, goodness and truth. The same grounds have led various Christians to assert that the natural creation must have been distorted by a spirit of evil, but this is another instance of argument from particular designs in nature. A truer attitude for the Christian, surely, was that of Dr. Pusey: "What are we, that we should object to any mode of creation, as unbefitting our Creator?"

At the present day, nearly all evolutionary biologists fully accept natural selection as the main means of animal evolution, but various other writers, both Christian and agnostic, have continued to advocate Creative Evolution. Professor Polanyi, for instance, conceiving the animal world as "a continuous ascending evolutionary achievement" wrote that "the action of the ordering principle underlying such a persistent creative trend is necessarily overlooked or denied by the theory of natural selection, since it cannot be accounted for in terms of mutation plus natural selection", and the similar views of Teilhard de Chardin have been acclaimed as the book of the year, if not of the century. So one is led to ask why views so unacceptable to biological specialists should be so widely accepted by others. The reason may, I suggest, be different for Christians and agnostics, that Christians, still misunderstanding the metaphysical implications of natural selection, want to see evidence for theistic design in nature, while agnostics feel that Creative Evolution may provide the justification for human values which natural selection is incapable of doing.

In answer to the Christian difficulty, I may quote the Oxford theologian Dr. Mascall: "We need not worry that science describes the course of evolution in impersonal concepts; that is its job. What is reprehensible is any attempt to treat the scientific account as if it were a metaphysical one." Again "Perhaps some modern apologists have gone badly astray in looking for direct evidence of God's design in the evolutionary process. The truth may be that God is able to achieve his ends without that sort of design." He added that, "for Christian theism, no events are fortuitous in the ultimate metaphysical sense".

The agnostic objection, that natural selection cannot justify human values, requires longer treatment. Especially since the finding of fossil men and ape-men in Java, Peking and South Africa, no one can seriously doubt that man's body evolved by natural means. In addition, so much innate or instinctive behaviour has now been demonstrated in man, and so much learning and social behaviour in animals, that we may reasonably conclude that at least much of man's behaviour is a product of natural evolution. But what of man's special faculties, in particular his moral conduct? Herbert Spencer postulated that good

conduct was the more evolved conduct, while theories of "evolutionary ethics" have also been advocated by modern biologists such as Waddington and Sir Julian Huxley, Waddington saying in effect that the direction of evolution is good.

Two problems are involved, the origins and the value of morality. Many of man's social attitudes, including his desire to help his fellows, are so deep-seated, and find such obvious parallels in other social mammals, such as apes or dogs, that partly innate tendencies would seem to be involved, which have presumably been subject to a natural means of selection. This might be through selection of the tribe, pack or other social unit; for social behaviour must, on balance, increase the chances of survival of the group and hence of the individuals composing it. Further, there is some reason for suggesting that at least part of what we now call evil behaviour was behaviour which contributed to individual survival in the past but which came to be selected against after men started to live in groups. However, all that has been said so far refers to social behaviour, not to moral conduct, and between them there is a great difference. The worker ant is social, but not moral, while the dog is social and we hesitate about a moral faculty, but probably decide against it.

Moral conduct is involved only when a genuine choice between actions is possible. We hold that man has free-will, through introspection and through what others tell us, while on the legal plane we accept as valid the distinction between a person being responsible or irresponsible for their actions, even though it may be hard to decide in certain cases. But no test or experiment can be devised to determine whether another animal has free-will. Sometimes we may see it delay before acting, but then the biologist may say that it was subject to conflicting drives, one of which proved strongest. (This type of analysis is itself open to criticism, but the important point is that all biological interpretations leave out the possibility of the animal possessing free-will.)

Free-will depends in turn on self-awareness, which likewise we have no scientific means of demonstrating in other animals. We sometimes speak of a pet dog being pleased or guilty, implying self-awareness, but we should strictly have said "as if

pleased or guilty", and we cannot pass beyond "as if". This is not necessarily to deny that other animals have self-awareness, but merely to say that we have no means of telling; and unless animals have free-will and self-awareness, we can hardly speak of their having moral conduct. The gap in knowledge seems unbridgeable. This still allows the evolutionist to assert that man evolved these peculiar faculties gradually from rudiments in other animals, but it does not allow him any direct evidence for this, and it allows others to claim that, so far as free-will, self-awareness and moral conduct are concerned, there is an absolute difference between man and all other animals. (The growth from unconscious behaviour to self-awareness in the human young does not necessarily afford a parallel with the evolutionary development of the species, since the baby's self-awareness must wait on the physical maturation of the brain.)

It is even harder to find a natural basis for the value than the origin of moral conduct. The essential difficulty was put long ago by T. H. Huxley, and many hold that it has never been answered, "Cosmic evolution", he wrote, "may teach us how the good and evil tendencies of man may have come about; but, in itself, it is incompetent to furnish any better reason why what we call good is preferable to what we call evil than we had before." Thus even if good behaviour is simply that which has contributed to the survival of the group, this provides no compelling reason why we ought to be good now, nor does it sufficiently explain why, when a man knows what is right, he so often chooses what he knows to be wrong. I think it fair to say that all the attempts so far made to explain moral values on evolutionary grounds have broken down, and many claim that such attempts will always fail because values come outside the terms of reference of science.

I suggested earlier that it was this difficulty that has particularly led various agnostic and other writers to reject natural selection. But the introduction of a Life Force does not really solve the difficulty, for we have no valid reason for postulating that such a Force, and the consequent direction of evolution, is necessarily good, while if the Life Force is good, the existence of evil is left unexplained. Indeed, while biologists have criticized Teilhard de Chardin for minimizing natural selection, theologians have done so for minimizing the problem of evil. Nor, so

far as I can see, is the evolution of human self-awareness made easier by Teilhard's postulate that "we are logically forced to assume the existence in rudimentary form . . . of some sort of psyche in every corpuscle, even in those . . . whose complexity is of such a low or modest order as to render it imperceptible". Indeed, I can attach no verifiable meaning to this statement, which seems to obscure the underlying problem by misuse of the word "psyche".

The difficulty in accepting a purely natural evolution for human faculties extends also to the power of abstract reasoning. As Darwin wrote: "But then arises the doubt, can the mind of man, which has, as I fully believe, been developed from a mind as low as that possessed by the lowest animal, be trusted when it draws such grand conclusions?" This difficulty, unlike evolutionary ethics, has rarely been mentioned by biologists, and there are similar, if less urgent, problems with respect to aesthetic values.

Hence the theory of evolution, so far as it has been developed, has not yet provided a satisfactory basis for truth, beauty and goodness, and many hold that no scientific theory can ever do so. This apparently leaves the Christian free to suppose that self-awareness, free-will, and the apprehension of truth, beauty and goodness, have come as a gift from God to each human soul, while evil has resulted, in Newman's words, from "some terrible aboriginal calamity". On this view, the principle of evolutionary continuity from ape to man so properly stressed by T. H. Huxley is broken, though on a spiritual rather than a natural plane. The agnostic, rejecting such views as myth, seems equally free to hold that man evolved gradually in every respect from other animals and wholly by natural means, acknowledging that not enough is yet known to determine the origin and value of these specially human faculties, though others might argue that this view provides too weak a basis for good conduct. There are also Christians who postulate a wholly gradual evolution of man from animals, some of them supposing that animals have an interior life, if not a soul, and others acknowledging ignorance as to the means involved. There are also atheists who consider moral values inexplicable in terms of natural evolution, leaving their basis unresolved. Each of these views involves unbridged, and perhaps

unbridgeable, gaps in knowledge, but it seems much better to admit these freely than to seek to bring all into a deceptive unity by the application of a theory outside its proper sphere:— such as Creative Evolution, which brings a pseudo-mystical concept into natural evolution, or Evolutionary Ethics, which interpret values in terms of natural survival. Enough has been said, I hope, to justify my statement that the conflict between Darwinism and religious belief has not been settled. Yet we can hardly afford to leave the settlement entirely to posterity, since we need a basis for our lives and actions now.

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(for general history and references see Lack, 1957)

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EXHIBITS IN THE LIBRARY

(*a*) A display of books on evolution, from the *R.I. Library*.

(*b*) New and recent publications, from *Oxford University Press*.

LUMINESCENCE: THE COLD LIGHT OF PHYSICS

By G. F. J. GARLICK, Ph.D., D.Sc.
Professor of Physics, University of Hull

Weekly Evening Meeting, Wednesday 25th May, 1960

P. H. Schwarzschild
Vice-President, in the Chair

Introduction

Luminescence has made important incursions into modern life, notably in such devices as the fluorescent lamp, the television tube screen and in less obvious ways such as fluorescent "whiteners" for laundry. The emission of light from bodies which absorb energy but remain at ordinary temperatures is generally known as *luminescence* the term being due originally to Wiedemann[1]. *Fluorescence* is most conveniently described as the luminescence emitted during absorption of energy or excitation, while *phosphorescence* is applied to the emission persisting after excitation is removed (demarcation line about 10^{-8} sec. after removal). The term *phosphor* is given to luminescent substances, being derived from the Greek and denoting a "*light carrier*". Luminescence is observed in gases when they are at a sufficiently low pressure and most favourably if they are subjected to an electrical discharge. It is not such a common phenomenon in liquids and solids and in fact special conditions are usually necessary for its occurrence. In most luminescent solids special atomic, ionic or molecular configurations exist in which luminescence processes can proceed undisturbed by the thermal vibrations of the surrounding atoms. Such entities are usually known as *luminescence centres*. Well-defined examples are the coordination group O-U-O in the uranyl salts and the platinocyanide group $Pt(CN)_4$ in the platinocyanides (first used as fluorescent screens for X radiography). In other cases, for example, in the zinc and cadmium sulphide phosphors, crystal lattice defects can function as centres (see Fig. 1) and may often need the presence of a specific impurity. The uranyl centre gives rise to well-defined spectra, particularly at low temperatures (see Fig. 2A) while the defect centre, in closer interaction with surrounding atoms or ions gives broad unresolved spectra, even at low temperatures (see Fig. 2B). By cooling

to low temperatures many substances become luminescent e.g. photographic film is brilliantly luminescent under ultra-violet radiation at liquid air temperature.

There are various ways of exciting luminescence, with ultra-

FIG. 1. Lattice defects in zinc sulphide phosphor.

violet light (photoluminescence, electrons (cathodoluminescence), particles, high energy radiation, mechanical strain and fracture (triboluminescence) or in some cases by the simple application of an electric field (electroluminescence) (see later). As to the classes of luminescent materials, very few inorganic

liquids are fluorescent, one exception being solutions of thallous salts, but many organic liquids show luminescence especially

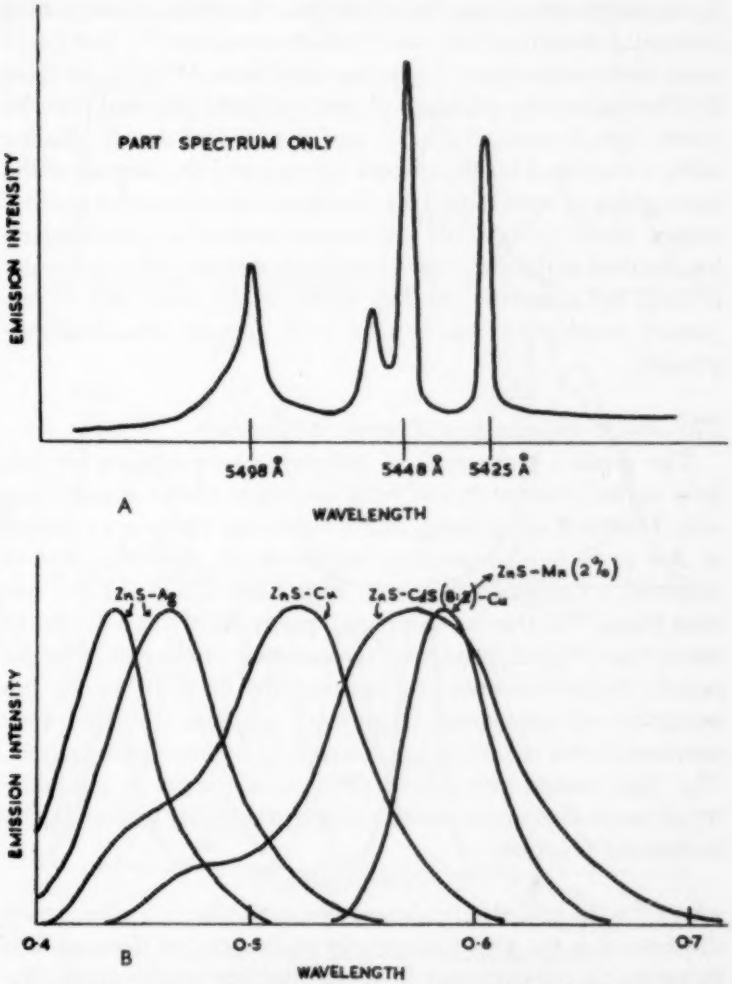

FIG. 2. (A) Luminescence spectrum for uranyl centre in $Cs_2 UO_2 Cl_4$ at 20°K. (B) Luminescence spectrum of zinc sulphide phosphor.

ring compounds such as benzene or solutions of aromatic hydrocarbons in such liquids as toluene or xylene. Some pure inorganic solids are luminescent such as diamond, uranyl salts, platino-

cyanides, tungstates etc. and more recently the solid halogens have been found to show luminescence in the near infra red region[2]. More usually inorganic phosphors are made luminescent by incorporation of specific impurities and lattice defects and by controlled departure from stoichiometry produced by heat treatment under oxidation or reduction conditions. Of these the most well known are the sulphides of zinc and cadmium used for television tube screens, the halo- and pyrophosphates of alkaline earth metals used for fluorescent lighting and the silicates of the same group of metals used e.g. in the screens of monitor oscilloscopes. Recently the study of emission outside the visible region has resulted in the discovery of many phosphors with ultra violet or infra red emission[3] (see Fig. 3) and in the latter case an important overlap has taken place with current semiconductor physics.

The storage and transport of energy in phosphors

The marked persistence of emission in some materials has long excited interest in analysing the origin of this storage process. Delays of up to many milliseconds can often be explained as due to forbidden electron transitions (in one case, that of diamond, a forbidden transition with a half life of 10^5 sec. has been found[4] but this is exceptional) particularly when the decay rate is relatively independent of temperature. In the case of longer period phosphorescence the cause of the delay is usually the excitation and subsequent trapping of electrons which are thus prevented from returning immediately to luminescence centres. The final escape and return of these electrons is markedly temperature dependent and the escape probability is given by the Boltzmann function:—

$$P = s.\exp(-/EkT)$$

where P is the probability of escape per unit time, s is a frequency constant, E is the activation energy or "depth" of the trap, k is Boltzmann's constant and T is the absolute temperature. Although this is a relatively simple function the incorporation of different values of trap depth and the sometimes complex kinetics of return of trapped electrons to centres after escape miake the derivation of a quantitative decay expression very difficult. The most powerful experimental method of analysing

the distribution of trapping states in a phosphor is not that of phosphorescence measurement (many life times in traps are years or more) but a technique known as the thermoluminescence or glow curve experiment, originally carried out by Urbach[5] in

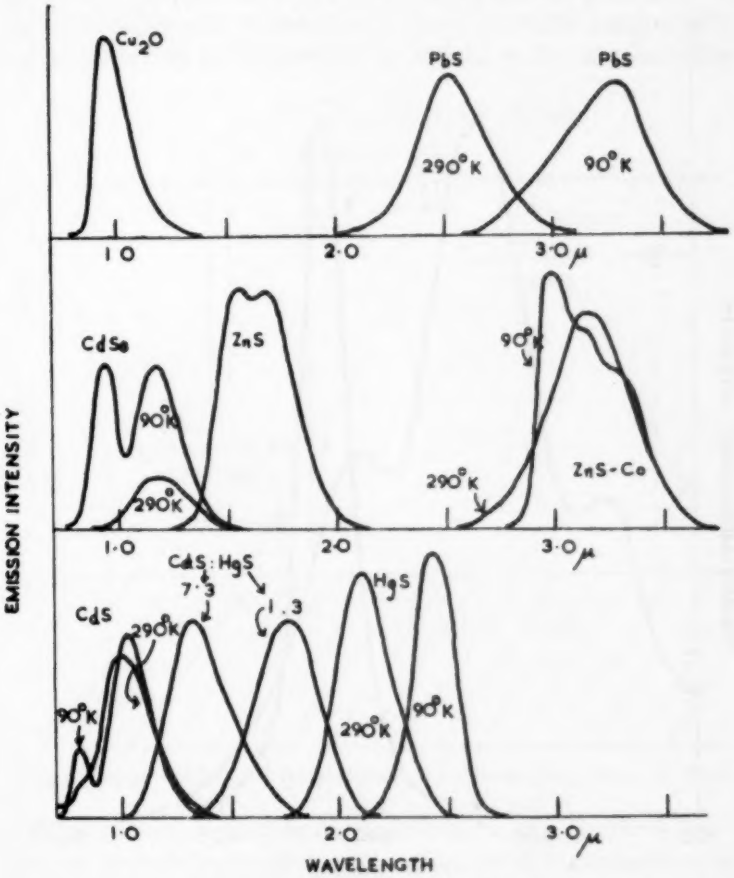

FIG. 3. Spectra of some infra-red emitting phosphors.

Vienna in 1932 but made into a sophisticated method for phosphors by Randall and Wilkins[6] who laid the foundations of the theoretical analysis still in use. The phosphor specimen is cooled to a low temperature (usually that of liquid air) excited and then warmed at a uniform rate in the dark. Electrons in

"shallow traps" are first released by the rise in temperature and later those in deeper traps. The resulting curve of emission against temperature, known as the glow curve can be shown to represent the distribution of traps in depth although its inter-

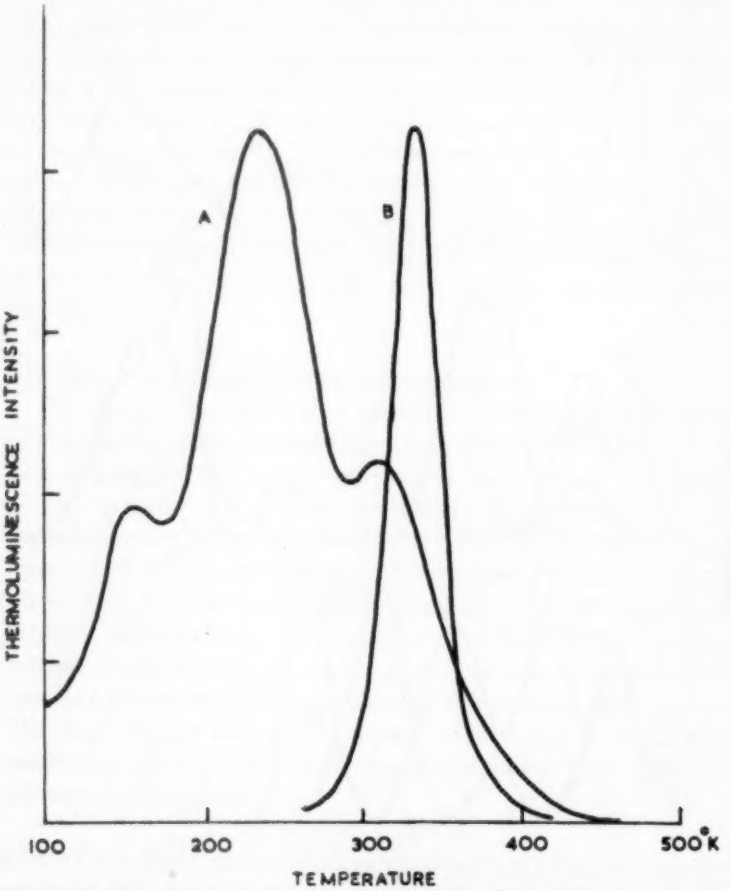

FIG. 4. Thermoluminescence curves for A. ZnS-Cu phosphor containing oxygen. B. Hypothetical curve for single depth of electron trap.

pretation is fraught with pitfalls for the beginner. Curve A of Fig. 4 gives a typical "glow curve" for a copper-chlorine activated zinc sulphide. The higher temperature peak is associated with a slight oxidation of the phosphor. Also included in the diagram is a theoretical glow curve (curve B) for a single value of

E in the probability of escape formula above. It is usually found in practice that E has a wide distribution but the narrowness of curve B shows that to a first approximation the glow at a particular temperature is due mainly to the escape of electrons from a particular "depth" of trap. During the release of electrons it is sometimes possible to measure a rise in electrical conductivity as the electrons move through the crystal to the luminescence

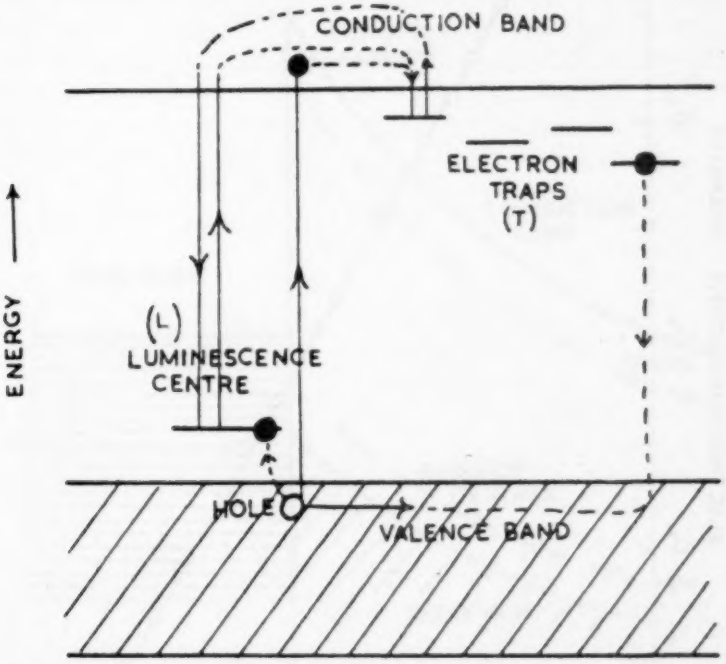

FIG. 5. Energy band model for phosphor; L luminescence centres : T traps.

centres. Detailed studies of luminescence and electrical properties provide a powerful combination for the investigation of the energy states due to imperfections in solids. Trapped electrons may also be ejected from their traps by long wavelength radiation (usually in the near infra red) and comparison of spectral efficiency for this with information from "glow curves" provides another useful combination of techniques for trap studies. If the optically freed electrons recombine with luminescence centres the resulting burst of emission is referred to as

stimulated luminescence; but if infra red frees electrons, but they recombine elsewhere in a non-radiative manner, the process is referred to as infra red quenching.

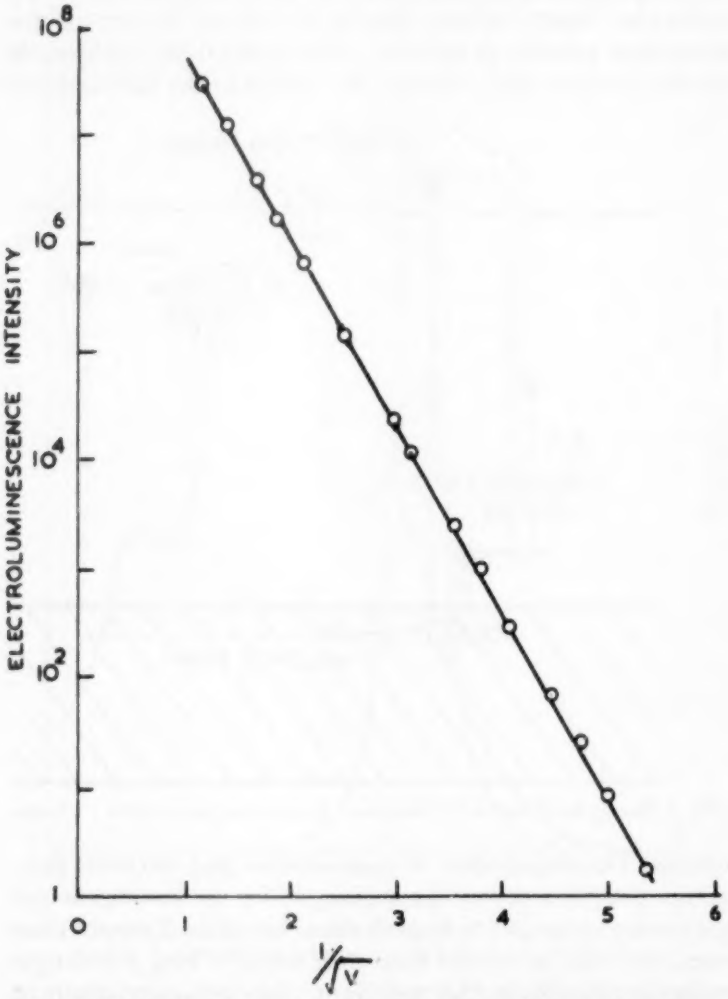

FIG. 6. Brightness voltage relation for an electro luminescent phosphor.

The simplest energy model that can be put forward to explain the phenomena of thermoluminescence and infra red stimulation and quenching is based on the modern picture of energy states

in crystalline solids. These states fall into bands of allowed energies separated by forbidden energy regions but regions in which lattice imperfections can give rise to discrete energy states. In such a model the luminescence centres and the trapping states can be represented as shown in Fig. 5. When unexcited the electrons of the crystal lie in the lowest band shown (these are the states of the original valence electrons of the atoms of the crystal)

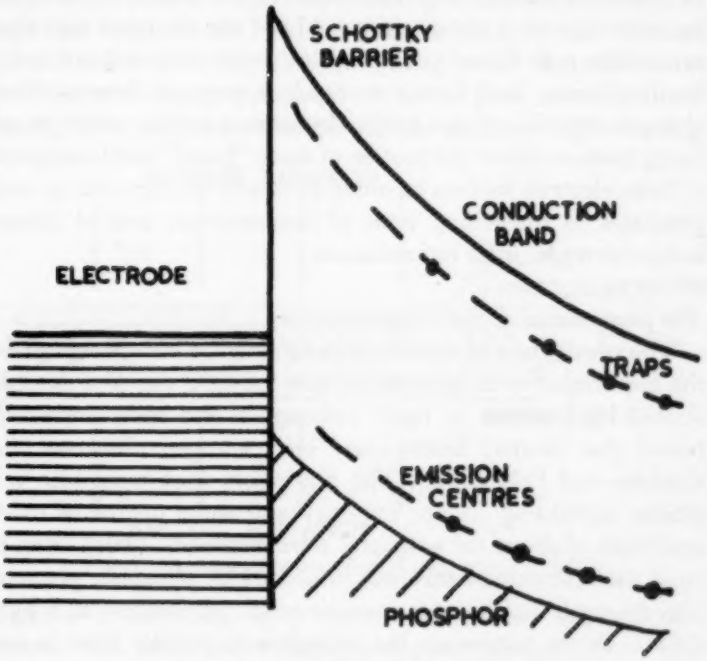

FIG. 7. Energy band model for electroluminescence.

and the emission centres also have electrons in their lowest states. Excitation, particularly ultra violet light or energetic particles, will raise electrons from this band into the upper band, known as the conduction band since here the electrons can move and contribute to a current through the crystal when an electric field is applied (photoconductivity). The electrons then either recombine with emission centres, which have lost their electrons to the band below, giving rise to immediate phosphorescence, or the electrons may be trapped in the trapping states shown just

below the conduction band. When they escape, either by thermal or optical means they have a chance of being retrapped or of recombining with emission centres to give luminescence. To explain the quenching action of infra red light we assume that this radiation raises electrons from the lower band to fill the emission centres and in doing so creates spaces in the band which can move and in fact function like electrons with a positive charge. These can move into the neighbourhood of the trapped electrons, become trapped in the electron field and the electrons may then recombine with these "positive holes" without giving out radiation but losing their excess energy in a series of thermal interchanges with the crystal lattice. In current studies attempts are being made to detect the motion of these "holes" and distinguish it from electron motion in order to clarify the kinetics of such processes as quenching both of luminescence and of photoconductivity by infra red radiation.

The phenomenon of electroluminescence

The production of sustained luminescence in a phosphor by the application of an alternating current field was first demonstrated by Destriau in 1936[7] although it had been previously found that electric fields could eject trapped electrons (the Gudden and Pohl effect). The phosphors used were zinc sulphides containing copper impurity and some degree of oxide and fields of about 10^4 volts/cm. were necessary. Much later, in 1949, electroluminescence was improved by phosphor preparation research and became a commercial proposition as a light source. In the latter case the phosphor in powder form is embedded in a resin and coated on to a glass panel having a conducting but transparent coating of metal or semiconductor next to the phosphor. The layer is backed by a metal coating and an alternating voltage applied across the layer. The emission brightness depends on voltage in an exponential manner, the exact form for many different cases being as follows:—

$$B = A \exp\left(\frac{-b}{\sqrt{V}}\right)$$

known as the Alfrey-Taylor relation[8], where B is the mean brightness, V is the r.m.s. applied voltage and A and b are

constants for a given system. Fig. 6 shows how this relation is followed over a wide range of brightness. Most of the emission occurs near to the electrodes and the usual explanation of the whole process is as follows:— When one electrode becomes negative a very high gradient of field is established near to it (in the form known as a Schottky barrier) and the electrons are pulled through it from the metal and accelerated into the phosphor. They produce more electrons by collisions and most of these get trapped. On field reversal the trapped electrons are ejected and return into the region near to the electrode to recombine with empty emission centres and give rise to luminescence. The energy band picture for one electrode region during

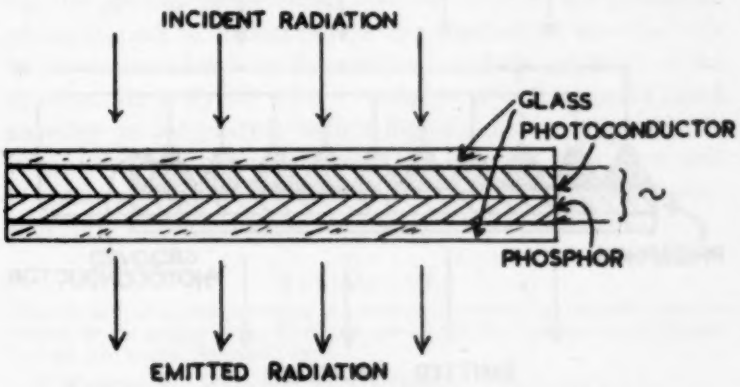

FIG. 8. Schematic diagram of solid state image amplifier.

injection is shown in Fig. 7. Since traps play some part in the process the latter is naturally temperature dependent. For similar reasons the emission is also dependent on the applied field frequency.

Because the emission is so non-linear with applied voltage electroluminescent panels offer possibilities as image systems if a primary image can be used to modulate the field across the layer. This has now been accomplished by making a "sandwich" system of an electroluminescent layer adjacent to which is a layer of photoconducting material, the applied voltage being across the whole arrangement as shown in Fig. 8. The impedance of the photoconductor is lowered by light or, for example, by X rays and this increases the effective voltage across the electrolumines-

cent layer thus raising its brightness. In this way it should be possible to intensify the original image if there is a net gain in the process. Detailed theoretical treatment of such a composite system shows that the capacitance of the photoconducting layer must be low relative to that of the electroluminescent layer and so to do this a simple layer system must be avoided. Fig. 9 shows the more complex grooved photoconductor system adopted by R.C.A. in their development of a solid state image amplifier. With panels of this type and with area of about a foot square

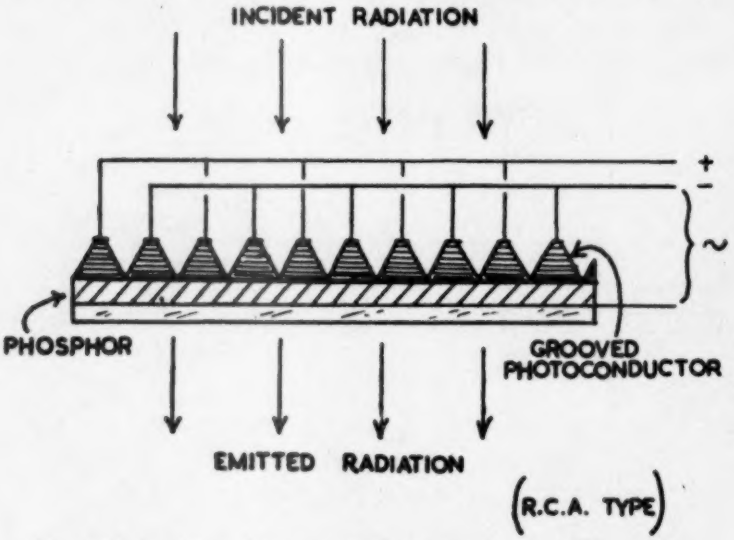

FIG. 9. Practical form of image amplifier with grooved photoconductor.

satisfactory intensified images with good resolution can be obtained. However, the main problem is the sluggish response of the best photoconductor available (cadmium sulphide) and much of the present research is directed towards the improvement of this section of the amplifier. Effective gains of up to one hundred are possible and a successful device would much reduce the doses necessary in X-ray diagnosis.

Application of luminescence materials to detection of nuclear radiation and particles

The first quantitative use of a phosphor for nuclear studies was

the employment of the zinc sulphide screen of a spinthariscope by Rutherford in his work which resulted in a verification of his theory of a nuclear atom. Instead of using the dark adapted eye the modern technique uses a photoelectric electron multiplier coupled with a large phosphor crystal, organic liquid or plastic. The stopping power of the solid or liquid detector is very much greater than that of the gas of a geiger counter (although the solid walls improve the geiger sensitivity. The great advantage of the scintillation counter, as the phosphor-photomultiplier combination is called, is the fast response time which can be in the millimicrosecond region. There is also a degree of proportional response to particle energy though resolution is not as good as for the gaseous proportional counter. One of the important advances made in nuclear physics as a result of the use of scintillation counters has been the verification of the existence of the neutrino. Recently, by using a phosphor crystal as a solid cloud chamber in conjunction with a highly sensitive photoelectric image converter of cascade type, the Russians have been able to obtain photographic images of the tracks of minimum ionization particles from nuclear reactions in the crystal.

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EXHIBITS IN THE LIBRARY

A display of a vacuum cryostat, liquid nitrogen cryostat, early apparatus for thermoluminescence measurements, infra-red phosphors, fluorescent lamp phosophors, single crystals of zinc and cadmium, specimens of cadmium sulphide crystals and mountings, and charts and diagrams illustrating luminescence, arranged by *Professor G. F. J. Garlick* with contributions from *A. E. I. Research Laboratories, Harlow* and *Thorn Electrical Industries, Enfield.*

SOME SOUTH ATLANTIC ISLANDS

By J. B. CRAGG, M.Sc.
Professor of Zoology, Durham Colleges in the University of Durham

Weekly Evening Meeting, Wednesday 8th June, 1960

H. D. Anthony, M.A., B.Sc., Ph.D.
Vice-President, in the Chair

ABOUT thirty years ago it was estimated that evergreen tropical rain-forest formed approximately half of the world's total of forest lands. This broad green belt running through the wet tropics contained a tremendous range of plant and animal species. Its plants had, in the past, given rise to much of the flora which characterizes our temperate regions. Now, that forest has been so maltreated by man that there is a danger that no more than remnants will survive the next fifty years. Man's inroads into the forest, his clearings and burnings, his introduced animals have so affected it that it is fair to say that his actions have altered the future course of plant evolution and with it the evolution of animals as well.

Man has, in fact, become the major evolutionary agent on the earth today. His destructive activities have, in the course of a life-time or so, brought about changes which in terms of range and irreversibility can only be matched by changes which before his emergence as a dominant species, took millions of years to accomplish. The fate of the tropical rain-forest is a dramatic example of man's destructiveness. It might be thought that islands and lands in the sub-antarctic and antarctic regions of the world would have escaped a similar fate. But that is not the case. Whilst acknowledging man's heroic activities in exploring the south, we must not forget the effects which he has had on the fauna and flora of what seem to be safe, isolated, islands.

Fig. 1 shows the main land areas included in the southern cold temperate and antarctic regions. The whole area is dominated by the ice and snow covered continental mass of Antarctica, some five million sq. miles in extent, an area which could contain the whole of Europe and a chunk of Africa. Away from the continent and lying north of the Antarctic Circle is the Antarctic Convergence. This oceanographer's line represents the boundary zone where the cold, mineral-rich Antarctic waters sink below the

warmer sub-Antarctic waters. At this frontier, water temperatures fall some 2 to 3°C in a relatively short distance and the distribution of many marine species is affected by the existence of this zone.

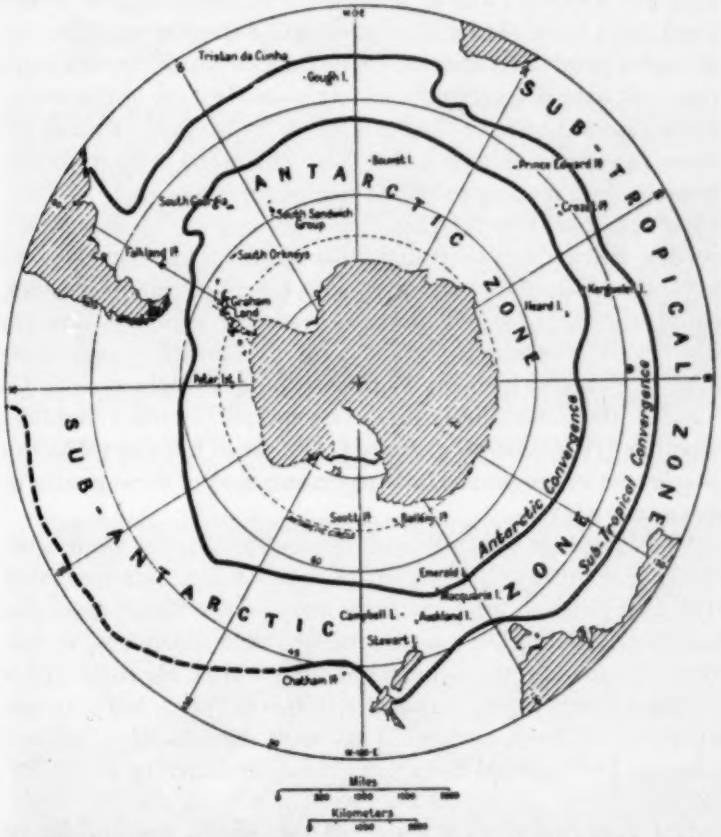


FIG. 1. Zones of surface water, and their convergencies, south-polar projection. (Reproduced by permission from *Oceanic Birds of South America*, by R. C. Murphy. Macmillan, New York, 1936.).

Before dealing with the Falklands, South Georgia and the South Orkneys, it is worth while considering the biological characteristics of Tristan da Cunha and Gough Island. These islands have a relatively mild climate, frosts, for example, do not occur at sea-level, and they have been free from the effects of

glaciation for a much longer period than the other groups of islands. Thus, some of the organisms associated with them have become highly specialised island forms.

Tristan da Cunha is an almost perfect volcanic cone, 6,750 ft high and about 8 miles in diameter. Permanent human settlement dates from 1810 and man has had a tremendous effect on its native plants and animals. Of its flora of 70 odd species more than half have been introduced either accidentally or intentionally by man. The terrestrial animals have also been affected. Of some 130 species at least a third are considered to be introductions which have resulted from man's activities.

Gough Island is 230 miles south east from Tristan, much smaller and never permanently occupied by man, it provides some information on what man with his usual camp-followers, cattle, sheep, goats and of course rats and cats, has done to Tristan. The island is fringed with the large Tussock grass (*Poa flabellata*) which must at one time have been present on Tristan. Its animal life includes two species of bird, a flightless moorhen (*Porphyriornis c. comeri*) and a small bunting (*Rowettia goughensis*) which are the only representatives of these genera in existence today.

The Falklands which lie some 12 degrees further south than Gough Island have a relatively poor fauna and flora compared with that existing some 300 miles away on the South American mainland. Charles Darwin who reached the Falklands in March, 1834, summed up their climate in a few words. He compared it with conditions at 1000 to 2000 ft. in North Wales, but with less sunshine, less frost, more wind and more rain. An adequate description, I feel, except that Darwin overestimated the Falklands' rainfall.

In Darwin's day, wild cattle and wild horses, descendants of animals taken to the islands by the first settlers in 1764, were still to be seen. The cattle which had numbered 80,000 at the end of the eighteenth century, were being slaughtered to make way for sheep. Darwin with a touch of evolutionary foresight suggested that the horses might well give rise to a southern equivalent of the Shetland pony, but both horses and cattle are now extinct. Darwin was particularly interested in the so-called Falkland Island Fox. How this carnivorous mammal had reached

A. Blue-eyed Shags (*P. atriceps*) at North Point, Signy Island, South Orkneys. Coronation Island is in the background. (Reproduced by courtesy of the *Falkland Islands Dependencies Survey*).

B. The Whaling Station at Grytriken, South Georgia. (Reproduced by courtesy of *F.I.D.S.*).

PLATE I

the islands was a mystery. It was already being persecuted, and Darwin forecast that it would suffer the same fate as the Dodo: forty years later, Darwin's words came true.

There can be few remote places which have been visited by so many outstanding scientists as have the Falklands. Darwin was neither the first nor the last. The French settlers who established Port Louis in 1764 were led by Louis Antoine de Bougainville who, at the age of 23, had been elected a Fellow of the Royal Society for a treatise on the integral calculus. J. D. Hooker, as a young surgeon with the *Erebus* and *Terror* collected plants on the Falklands for his famous *Flora Antarctica*. T. H. Huxley on the *Rattlesnake* spent some uncomfortable and biologically unrewarding days at Port Stanley. The *Challenger* with its illustrious collection of Victorian scientists called at the islands. Nordenskjöld on the *Antarctic* spent some time there. It is of special interest to recall that one of Nordenskjöld's companions in 1902 was Carl Skottsberg, now a world authority on the botany of the southern regions. As recently as December, 1959 he gave a stimulating paper in London on the botany of the southern cold temperate zone.

The Falklands, for all practical purposes, treeless islands, carry an extremely interesting fauna and flora. Much of their surface is reminiscent of British moorland but the actual species of plants which go to make up the flora are different. The yellow-green patches of vegetation are largely made up of a coarse grass—*Cortaderia*. The brown patches are *Empetrum rubrum*, Diddle-dee to give it its charming Falkland name, one of the crowberry plants which looks not unlike our own heather. The vivid greens of the landscape are often bogs which have a very different plant composition from bogs in this country. The moorland surface is broken by tough, slow-weathering quartzite ridges and the slopes of many hills are boulder-strewn to form what Darwin described as "streams of stone" in which, as he pointed out, some of the boulders are as big as churches. These "streams", relatively devoid of plant cover, are the relics of sub-glacial conditions. The Falklands were not glaciated in the Pleistocene, but under the effects of frost-heaving, solifluction and soil creep, rocks once hidden by soil, have been laid bare.

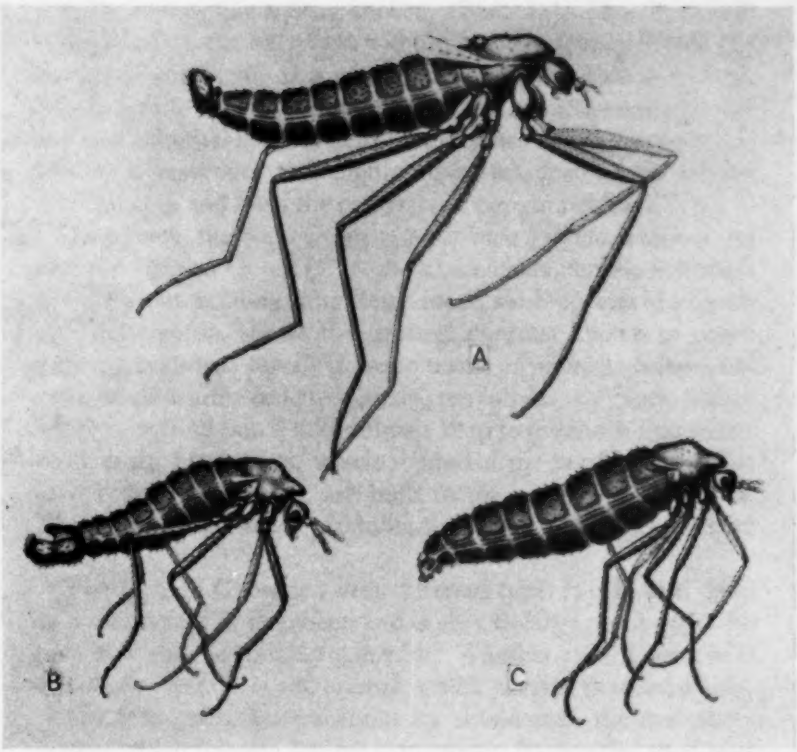
Tussock grass (*Poa flabellata*) still grows in abundance on

some of the smaller islands where sheep have not been introduced. It forms huge stools, in places 8 to 10 ft. high with grass blades growing out from a thick peaty core. Tussock grass is typically associated with well-drained ground on the coasts, and from the sea a tussock area has been likened to a plantation of palm trees. In various places there appears to be a close relationship between penguins, seals and tussock. William Davies has attributed the success of tussock to the activities of penguins and seals which make pathways through it and enrich the ground with their excreta. J. D. Hooker saw high hopes for it as a fodder plant of high quality. In his day, as well as clothing the smaller islands it formed a broad fringe around the larger areas. But, capable of withstanding the grazing of cattle and horses, it succumbs to the nibbling of sheep. There can be little doubt that sheep have been responsible for its virtual disappearance from the main islands.

This disappearance of Tussock is not confined to the Falklands. In all probability it occurred on Tristan. Its road to extinction was broadly hinted at by Cunningham in the 1860's for he described how its abundance in the Straits of Magellan had been considerably reduced in the thirty year interval since Hooker's visit.

The fate of this Tussock grass is just one example of what is happening to characteristic plant species of the southern cold zone. From the lists compiled by Darwin, Hooker and Skottsberg and from the comments of more recent visitors, it is only too evident that the native plants of the Falklands are being reduced in number whilst the number of man-introduced species has risen.

The Falklands carry a rich and varied bird fauna and their ties with the south are vividly shown in the sea bird colonies around their coasts. On Kidney Island I was able to see colonies of the Rockhopper penguin (*Eudyptes crestatus*) and the Jackass (really the Magellan penguin (*Spheniscus magellanicus*) and not the Jackass penguin of South Africa). The former nest precariously on steep cliffs and the noise they make has been compared with that of "thousands of wheelbarrows badly in need of grease being pushed around at full speed". King Shags (*Phalacrocorax albiventer*) nest in close proximity to the Rockhoppers and women's meetings in the Falklands have been described as



Belgica antarctica (Fig. B the male and Fig. C the female) a flightless midge 3 to 4 mm long which lives and breeds within the antarctic zone. Fig. A shows *Jacobsiella magellanica*, a related form, rather larger and with better developed wings, occurring in the southernmost regions of South America. (From: *Expédition Antarctique Belge. Rapports Scientifiques. Zoologie* (*Insectes*). 1906).

PLATE II

making a noise like a Shag rookery (Plate IA). The Sheathbill (*Chionis alba*), the only bird without webbed feet to invade the Antarctic continent, is a winter visitor to the Falklands with non-breeding individuals remaining around the coasts in the summer months. In spite of its almost dove-like appearance this bird is a scavenger in penguin rookeries, feeding on refuse, excreta, eggs and even the carcasses of penguin chicks.

Two geese, the Kelp Goose (*Chloephaga hybrida malvinarum*) and the Upland Goose (*C. p. picta*) are characteristic members of the Falklands fauna. The Kelp Goose, a sub-species of a South American goose, shows the greatest contrast known to occur between male and female geese in terms of plumage colour, the male snow-white, and the female, predominantly black with a white rump and tail. These animals keep to the shore-line where their down-lined nests, which reminded me very much of our own Eider Duck's nest, are built in the base of the Tussock. Their diet of seaweed, produces flesh and eggs quite unfit to eat.

The Upland Goose is a very different type. It is looked upon as a competitor of the sheep and is shot in large numbers. Both bird and eggs are highly palatable. Whether it will survive is uncertain; but it is an animal which merits detailed study. Nothing is really known about its abundance, the mortality-factors which operate against it in nature, its detailed food preferences and its long-term effects on the herbage. It is possible, for example, that at certain densities it might be found to benefit sheep pasturage.

Marine mammals occur around the Falklands. The Falkland Island Sea-Lion, in reality a population of the South American sea-lion, which breeds on the Falklands, probably numbers about half a million and fur seal numbers are recovering after their general decimation in the nineteenth century.

For many Englishmen South Georgia represents the gateway to the Antarctic (Plate IB). Captain Cook named the island, in the words of Forster ". . after the monarch who had set on foot our expedition, solely for the improvement of science. . . ." Whilst science may have been the major objective, Cook's discoveries resulted in the development of whaling, sealing and penguin hunting around South Georgia. In the fifty years which

followed Cook's voyage the Fur Seal (*Arctocephalus gazella*) in particular, was persecuted and brought to the point of extinction. Weddell estimated that well over one million seals had been killed at South Georgia within that period. Shocking as these figures are, we can only wonder at the insatiable demand for the animal's skin and marvel at the courage and endurance of those who carried out the kill, traversing some of the bitterest, storm-swept, seas of the world.

The terrestrial fauna and flora, if we exclude the sea birds, is poor in species. There are about twenty species of flowering plants, the bulk of them grasses, about one hundred mosses and perhaps the same number of lichens and liverworts. The only obvious invertebrates are six species of two-winged fly (Plate II), six beetles, two spiders and one earthworm. The island has not been fully explored and it is more than likely that some additions will be made to this list. Whatever the additions, however, the overall picture will be that of a fauna and flora of a particularly impoverished kind, struggling for survival on a sterile landscape which is still emerging from an ice-age.

Whereas the Falklands, on the warm side of the Antarctic convergence and of course, nearly one thousand miles nearer to South America, have at least 30 to 35 breeding species of land birds, South Georgia has only two. These are the South Georgian teal (*Anas g. georgica*) and the small South Georgian pipit (*Anthus antarcticus*). Both of these forms are closely related to South American species, the South Georgian teal being a subspecies of the Brown Pintail (*Anas georgica spinicauda*). Their origin is obvious but what I think noteworthy is that these two forms have, in a relatively short period, developed at least subspecific if not specific status. Various bird species must, from time to time, reach South Georgia from South America and yet only these two have been successful in establishing indigenous populations.

South Georgia carries extensive sea bird colonies and recently the Albatrosses on South Georgia (Plate IIIA) have received special attention from a three-man expedition led by Lance Tickell and in part supported by the Falkland Islands Dependencies Survey. In a single season's work they ringed almost 7000 birds, an achievement of considerable merit which will be

A. A Sooty Albatross and her chick at South Georgia. (Reproduced by courtesy of *F.I.D.S.*).

B. Elephant Seals at South Georgia. (Reproduced by courtesy of *F.I.D.S.*).

PLATE III

of great value to ornithologists in the future. Of particular interest was the information which they collected on the life history of the Wandering Albatross. When they arrived at Bird Island in November, young birds produced during the previous season had not begun to fly. These youngsters were being fed by visiting adults and Tickell's observations strongly suggest that the old idea of the Wandering Albatross chick remaining at the nest for several months without being fed is wrong. I hesitate to destroy too many myths but I cannot resist pointing out that under a tape-measure, the exceptional wing-span reads twelve not twenty feet. As for the fate of Coleridge's ancient mariner, the Albatross as food has certainly not been ignored by sealers and others who have crossed the southern oceans. The three smaller species of Albatross also breed on South Georgia and a comparative study of their breeding and feeding habits should provide valuable information on the ecological separation of these species and their abundance.

Elephant seals (*Mirounga leonina*) which were scarce earlier in the century are again being killed for commercial purposes (Plate IIIB). Compared with whaling where practically every part of the organism is put to some commercial use, sealing provides only blubber and the rest of the carcass is left on the shore for the Skuas (Plate IV) and other birds to clean up.

Whaling is carried on from shore-based stations which send out catchers and from factory-ships which are supplied at sea by catchers. In spite of international regulations for the control of whaling there is little doubt that the stocks of several species are being depleted. Unless more stringent regulations are accepted by all countries which hunt whales, or some alternative source is found for the commercially valuable whale products, particularly the oils which go to make our margarine, there is a great danger that the list of vanished or vanishing species is going to be extended. There is, I suppose, some hope that the mere expense of catching fewer and fewer whales will itself check the amount of killing before extinction is the only outcome, as it did in the case of the fur-seal and elephant seal but it would be dangerous to rely on such a possibility.

As one sealing area was worked out, other breeding grounds were found and plundered. The South Shetlands, for example,

were discovered in 1819 and in the following year one of some forty to fifty sealing vessels which visited them brought back more than 16,000 fur-seal skins. By the summer of 1822 the seals were almost non-existent.

In this search for seals, George Powell sighted the South Orkneys in December, 1821. Weddell, unaware of Powell's discovery, landed on them nine weeks later and gave them their name. There were few seals on the islands and so they tended to be neglected. However, in 1903, the Scottish National Antarctic Expedition visited them and laid the foundations of our modern knowledge of the group. It was this expedition which established the weather station on Laurie Island which since 1904 has been manned continuously by Argentinians and has thus provided valuable weather information for that sector of the Antarctic.

British scientific activities in the South Orkneys were renewed in 1946 with the establishment of a base on Laurie Island by the Falkland Islands Dependencies Survey. The following year the base was transferred to Signy, a small island only four miles long and situated to the south of Coronation Island. Since that time, Signy as Base H of F.I.D.S. has played a very important part in the development of scientific work on the fringes of the Antarctic continent and it is ideally situated as a centre for biological research under antarctic conditions.

Some 6° further south than South Georgia, the average mean air temperature in the South Orkneys is approximately —1°C. In spite of this, two flowering plants manage to survive along with an extensive bryophyte flora. The fauna, apart from the birds, is mainly limited to small forms such as Collembola and mites. The shores have a sublittoral fauna which has scarcely been studied. Of the various F.I.D.S. studies on Signy the bird work deserves special attention. It was in 1948 that Laws ringed the first batch of Giant Petrel chicks and it seemed unlikely that much could be expected in the way of ringing returns from such an isolated place. Within nine weeks of leaving the nest, however, one of the ringed chicks was taken alive in West Australia, 10,000 miles from its breeding place. Since those early days a great deal has been learnt about bird movements within the southern hemisphere. Young Giant Petrels ringed at various sites in the south have turned up in Australia, New Zealand,

A Skua. (Reproduced by courtesy of *F.I.D.S.*).

PLATE IV

South Africa and South America. The Signy-Australia run is one of the most rapid trips, some thirty recoveries having been made within the first four months after ringing. It is now clear that these and some other bird species move completely round the world in the West Wind zone.

Penguin colonies are a characteristic feature of the Signy scene. Studies on Adelie penguins (*Pygoscelis adeliae*) at Signy have helped to clear up a number of important points about penguin behaviour. The Adelie (Plate VA) is a truly Antarctic bird with colonies on the continent itself. The South Orkneys in fact represent the northern fringe of its breeding area. The Chinstrap (*P. antarctica*) on the other hand has a more restricted distribution (Plate VB). It does not go so far south and its centres of breeding are in the South Orkneys and South Sandwich groups. Some million Chinstraps probably breed on Laurie Island. Of the other penguins associated with Signy Island, the Gentoo (*P. papua*) has a circumpolar distribution and breeds as far north as the Falklands. Some mention must be made of the Macaroni penguin (*Eudyptes chrysolophus*) which appears to be increasing its breeding range. Information on the growth of its colonies, changes in the age-structure of colonies and the movements of birds in the process of establishing new colonies, should form a valuable contribution to our knowledge of the colonial habit in sea birds.

The Antarctic region is one of contrasts. There is the amazing wealth of marine life seen in the form of whales, seals and seabirds which in itself is an indication of the hidden wealth of small organisms in the Southern Oceans. Contrasted with this wealth of the sea is the poverty of the land in terms both of variety of species and in actual numbers of organisms. About marine life we know a great deal thanks to many expeditions and not least to the continuous work of the *Discovery* investigations which started in the mid-twenties. The land animals have received only fleeting attention. They should be studied in detail and efforts should be made to protect them against further damage from man-made introductions. These simple associations of animals and plants occurring under rigorous environmental conditions offer exceptional opportunities for investigating ecological relationships.

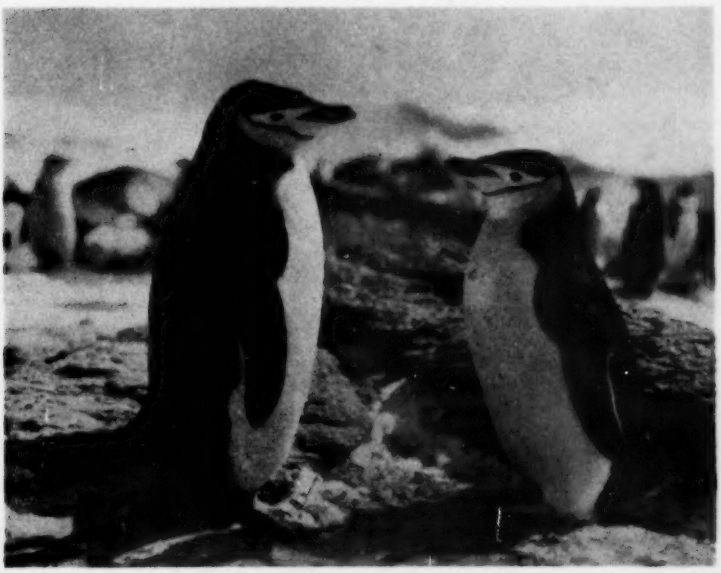
The nature and origin of these terrestrial animals and plants has presented biologists with a number of puzzles. J. D. Hooker, to explain some of the peculiarities of distribution suggested that the Antarctic continent had been connected to the major continents in the southern hemisphere by land bridges. Charles Darwin and Alfred Russel Wallace both favoured the claims of long-distance dispersal through the agencies of wind, ocean currents and of course carriage by birds or aquatic animals

From Tristan da Cunha to the South Orkneys, the dominant animals and plants are of South American origin. There can be little doubt that all of these islands in post-glacial times have been colonised by organisms which have traversed the southern ocean. The West Wind Drift has been a major factor in bringing about this colonisation. The northernmost islands have, however, a larger proportion of endemic forms than have the islands further south. This is to be expected since they have been free from ice-cover or from the effects of neighbouring ice-sheets, for a much longer period of time.

It has been suggested that even on South Georgia and the South Orkneys some of the mosses and lichens are relics of a more extensive flora which existed there in pre-glacial times. This raises the problem of the nature of the pre-glacial fauna and flora not only of the sub-antarctic and antarctic zones but of a large part of the southern hemisphere. If we consider the existing terrestrial organisms of the southern regions as a whole, we recognise that there are close links between the faunas and floras of all the southern continents. Equally important is the absence of typical northern genera. Among plants, the *Nothofagus* species and some of the Tussock grasses are southern forms unrepresented in the northern hemisphere. The weevils of the cold southern temperate zone are marked off from northern genera and form a much more important element in the terrestrial faunas of the south than do their counterparts in the north. Information of this kind which indicates a distinctive southern fauna and flora also suggests that the centre of origin of at least some of these forms, in the long distant past, may have been the Antarctic continent itself.

The past history of Antarctica and its effects on the present distributions of animals and plants is bound up with all the

A. A colony of Adelie Penguins at North Point, Signy Island. (Reproduced by courtesy of *F.I.D.S.*).



B. Ringed or Chinstrap Penguins at Gourlay Peninsular, Signy Island. (Reproduced by courtesy of *F.I.D.S.*).

PLATE V

problems concerned with continental drift. In fact the Antarctic regions offer tremendous opportunities for mixing up scientists of all types. The zoologist, botanist, palaeontologist, geophysicist, meteorologist, oceanographer, glaciologist and geographer, each has his sectional interest in Antarctica, but overriding the special problems of the separate disciplines are the broad problems associated with explaining the past and if possible forecasting the future of the Antarctic continent.

EXHIBITS IN THE LIBRARY

(*a*) Skins and mounted specimens of a Fur Seal, Wilson's Petrel, Adélie Penguin, Cape Pigeon, Giant Petrel, Falkland Island Steamer Duck, South Georgian Teal, South American Pintail, South Georgian Pipit and a Falkland Island Upland Goose, lent by *The Director, British Museum (Natural History)*.

(*b*) Mounted specimen of an Emperor Penguin with egg, a diorama of an Antarctic sledge scene and a selection of photographs of the Falkland Islands Dependencies, lent by *The Director, Falkland Islands Dependencies Survey*.

(*c*) Photographs of the Falkland Islands, lent by the *Falkland Islands Company*.

THE STRENGTH OF SOLIDS

By A. H. COTTRELL, M.A., Ph.D., F.R.S.
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Weekly Evening Meeting, Wednesday 15th June, 1960

Professor L. A. Jordan, C.B.E., D.Sc., F.R.I.C.
Vice-President, in the Chair

Two kinds of strength

I have been interested for some time in what makes things strong; makes them resist forces without giving way. The practical importance of this subject is quite obvious, not only in engineering but in the functioning of our bones and muscles. It is also interesting scientifically because it has to do in the end with the forces between atoms and molecules.

There are two distinct kinds of strength; strength against plastic yielding (i.e. hardness) and strength against fracture. Soft clay is weak; it can be worked plastically into different shapes and yields under its own weight. Glass is hard, springy, and able to scratch most metals. We do not build bridges from it, however, because it is weak against fracture, as may easily be seen by dropping a piece on the floor. We may say, paradoxically, that glass is weak because it is strong, for we find that strength against yielding and strength against fracture generally run counter to each other in materials. If you harden clay by baking it you eventually produce a brittle material that crumbles easily. You have then largely destroyed its resistance to fracture by raising its resistance to yielding. We see the same effect in the bending of young bones and the breaking of old ones. Also in metals. Ordinary carbon steel is softened by annealing, i.e. by heating it to a bright red heat and then cooling it slowly. But by rapidly cooling it, e.g. by quenching it in water, we can make it very hard and brittle, so that it easily snaps. The art of tempering steel is to blend these two opposing properties, by skilful heat-treatment, so that the metal is fairly hard but not so extremely hard as to be weak against fracture.

Materials such as metals are valuable because both kinds of strength can be blended into them. While the applied forces remain below a certain limit—the yield strength—they are as elastic as glass and preserve their shape with the precision re-

quired for engineering construction. But when overstressed they become plastic and do not break in a brittle manner. They have the same ability as soft clay to yield plastically rather than to break, but they improve on soft clay by keeping this property in reserve until large forces are applied. By contrast, glass goes completely to one extreme or other. At room temperature it is hard and brittle; at high temperature it runs as a viscous liquid; and there is only a narrow range of temperatures in which it changes over from being too hard to being too soft.

Brittle strength

Why are brittle materials weak? This is of course not a matter of weak atomic forces. The weakness of such forces, in for example waxes and lubricants, is easily recognised by the high vapour pressures possessed by such materials. The heat motion in matter provides a means of testing the strength of the material on an atomic scale. The higher the vapour pressure, at a given temperature, the weaker are the interatomic or intermolecular forces. Judged in this way, glass is undoubtedly a strong material since its vapour pressure is very low.

One can, in fact, estimate the strengths of these forces quite reliably. Such calculations can be made to various degrees of accuracy and complexity, but they all agree on one broad point, which is that these forces are really strong only when one atom is well within one atomic diameter of another. For a very rough estimate, then, we could say that the tensile force between two atoms is greatest when the distance between them is about one-half of an atomic radius. Regarding these atoms as two spheres in contact, the normal distance between their centres is two atomic radii. Hence the tensile strain (i.e. increase in distance divided by initial distance) at the "breaking point" is about 0.25. We know roughly what force is neeed for this from the Young's Modulus of the material, i.e. the ratio of stress to strain at low loads. For glass this is 10,000,000 pounds per sq.in. Hence the strength of the molecular bonds in glass is, very roughly, 2,500,000 p.s.i. By contrast, the strength of ordinary window glass is only about 10,000 p.s.i.

We have to recognise then that a material may be strongly held together by atomic forces and yet still be weak. The reason

is that most materials contain various small sharp notches or cracks, and the applied forces concentrate intensively at the tips of these. As may easily be seen by stretching a piece of rubber with a slit in it, an applied force springs the faces of a crack apart rather as if they were being forced open by a sharp-pointed wedge. The sharp peak of force that would exist at the tip of such a wedge is directly analogous to the sharp concentration of applied force produced by the springing apart of the faces of the crack. It is in fact quite easy to demonstrate these large stress concentrations experimentally. One method is to use photo-elasticity, in which interference colours form at the tip of a crack in a transparent material and indicate the state of stress there. The systematic study of these colours enables the stress fields round cracks to be measured.

The theory of the effects of such cracks in brittle materials was developed by Professor Inglis and Dr. Griffith. The stress at the tip of a crack is raised by a factor approximately equal to $\sqrt{\left(\frac{\text{length of crack}}{\text{radius of crack tip}}\right)}$ and this can be very large, particularly when the crack is only one atom wide at its tip. For instance, if the atomic radius is 10^{-8} cm a crack 0.01 cm long would enlarge the stress one-thousandfold at its tip. Thus the atomic bond strength could be reached at the tip, and fracture could occur there, while the applied forces were still only one-thousandth of what might be expected from the ideal strength of the material. This is why brittle materials are weak.

As regards evidence for cracks, the larger cracks can of course be seen quite easily although special methods are required to make the smaller ones (e.g. 10^{-4} cm in glass) visible. The cracks that weaken glass are usually formed at the surface by chemical attack from the atmosphere. Glass can be strengthened by cooling it from high temperatures in such a way as to set up compressive strains in the surface layers. These close up any surface cracks that would otherwise form and the material is much stronger. This idea is exploited in motor car windscreens and also in pottery glazes. Glazes are used that have smaller coefficients of thermal expansion than the underlying material, so that they go into compression on cooling from high temperatures.

Flawless materials and limiting strengths

There is spectacular evidence for both the crack theory and the very large ideal strengths of materials. Griffith demonstrated that extremely fine glass filaments (10^{-4} cm diameter), freshly drawn from the hot material, are immensely strong. They can withstand stresses of about 1 million p.s.i.; at this rate, for example, a thread slightly over 0.01 inch diameter could support the weight of a man. This very high strength has been demonstrated to be a property of all solids when prepared in the form of fine "whiskers". Such specimens are virtually free from harmful cracks and similar flaws, and in them the inherently high strengths of the atomic bonds are used to the full. It is usually impossible to prepare large thick specimens free from damaging flaws but this has been achieved in a few cases. Flawless crystals of germanium and silicon, of immense strength, have now been prepared in sizes up to 0.5 inch diameter.

Such results are very exciting, both practically and fundamentally. Practically, because they show that immensely strong materials are feasible. Fundamentally, because they provide a direct means of measuring the strengths of forces between atoms. Such measurements have in fact largely confirmed the theoretical calculations.

Although the strengths of these flawless materials set an ideal to which all designers of engineering materials aspire, it seems unlikely that large flawless pieces will ever be used as structural components in engineering. They are extremely difficult and expensive to make and, in service, there would always be the danger of flaws being formed on them through, for example, chemical attack or through the impacts of flying specks of sand or grit.

No, the practical approach is to admit the existence of cracks and notches and to try to render them innocuous. Suppose that we are stretching a rod in tension and imagine that it consists of a bundle of parallel, longitudinal, fibres joined together along their lengths by some adhesive or solder. If there is a transverse notch in the rod, cutting across a number of these fibres, the forces from the cut fibres can be transmitted to the fibres at the tip only by passing as shearing forces through the layers of adhesive that join one fibre to the next. If this adhesive has a fairly

low resistance to shear (but a strong adhesion), so that it can allow one fibre to slide along its neighbour to some extent, it will then be incapable of focussing the transmitted forces sharply at the tip of the notch. Instead, these forces will be transmitted at various points along the whole length of the fibres and so will be diffused over a large volume of material.

A reliable, strong, material will thus consist of a bundle of strong (i.e. hard and brittle) fibres joined together by some weaker adhesive, or by weaker atomic forces. This is in fact the structure of some of the best engineering materials, both natural and man-made. As regards natural materials we think of the fibrous proteins generally. As regards man-made materials we think of drawn metal wire, fibreglass, wrought iron, spun fibres, and rope. There are tremendous possibilities for developing this principle further, particularly by using fibres of materials with very strong atomic forces, e.g. refractory oxides and carbides. The table shows representative values of tensile strengths.

REPRESENTATIVE TENSILE STRENGTHS (p.s.i.)

Fibres and Wires

Graphite whiskers	up to 3,500,000
Iron whiskers	,, ,, 1,400,000
Silica fibres	,, ,, 900,000
Drawn tungsten wire	,, ,, 550,000
Ausformed steel wire	,, ,, 450,000
Drawn molybdenum wire	,, ,, 450,000
Piano wire (steel)	250,000—350,000
Ordinary steel wire	80,000—220,000
Flax (cellulose)	90,000—160,000
Drawn phosphor bronze wire	100,000—160,000
Drawn copper wire	30,000—80,000
Cotton (cellulose)	40,000—60,000
Silk (natural fibre)	50,000—60,000
Rayon	30,000—90,000
Rubber	30,000—90,000
Drawn aluminium wire	30,000—60,000
Catgut	60,000
Synthetic fibre (polyester)	35,000
Spider thread	27,000

Bulk Materials

Nickel-chrome steel	up to 230,000
Fibreglass	„ „ 200,000
Spring steel	140,000—160,000
Mild steel	60,000—80,000
Copper	17,000—70,000
Aluminium	15,000—40,000
Cast iron	15,000—40,000
Thermosetting plastics	6,000—20,000
Hemp rope	10,000—15,000
Hard woods	9000—16,000
Glass	4000—15,000
Thermoplastics	3500—11,000
Leather	4000—8000
Concrete	100—1000

Strength of ductile materials

One can be misled about the strengths of ductile materials. The practical approach is to take a bar of given cross-sectional area and find the greatest load it will withstand without breaking. The ratio of this load to the initial cross-sectional area is then called the ultimate tensile strength of the material. On a soft ductile metal this is not particularly large, e.g. 60,000 p.s.i. for iron. However, this is not the true breaking stress of the material. For, during the test, the cross-section steadily diminishes due to the plastic elongation of the material. The ultimate tensile strength is the point at which the loss of cross-sectional area predominates over the gain in strength due to the work hardening of the material. Beyond this point one part thins down to a narrow "neck". Fracture eventually occurs in the neck, at some quite high stress (300,000 psi for iron)—called the true breaking stress—but the load supported at this point is smaller than at the ultimate tensile strength because the cross-sectional area has become so small.

The strength of a ductile material thus depends on three things: (1) the yield stress, (2) the true breaking stress, (3) work hardening. The yield stress is the stress at which plastic flow begins. Work hardening is necessary, otherwise necking would begin at the yield stress, which would also be the ultimate strength. This last effect actually happens in some metals and alloys that have been hardened too much by, e.g., alloying or nuclear radiation.

Hard aluminium alloys as used in aircraft sometimes give trouble because they are unable to protect themselves, through work hardening, from failure by concentration of the plastic strain into one place.

Dislocations

We now understand a great deal about plastic deformation in crystalline solids. It usually takes place by slip in which the crystal layers (slip planes) slide over one another along definite crystal axes. The atoms in these layers do not all move simultaneously as if fastened to rigid sheets. Slip begins in one region of a slip plane, by the sliding of the atoms there through one atomic spacing over their neighbours on the other side of the plane. At this stage there then exists in the slip plane two regions, one slipped and one not yet slipped. The boundary between these is called a dislocation line. The slip then spreads over the unslipped part of the plane by the outward movement of the dislocation line, somewhat as a wave on a pond spreads outwards from a splash. A sequence of such dislocation lines spreads out from an active source of slip in a slip plane and their cumulative effect is to slide one layer over the next by many atomic spacings. The structures and properties of crystal dislocations have been studied intensively in recent years, both theoretically and experimentally, and a great deal is now known about them.

We are now quite sure that in ordinary engineering solids there are abundant sources of dislocations and that these dislocations can be very easily moved at all temperatures. Such materials are intrinsically soft and their yield strengths depend upon various obstacles placed in the path of these dislocations. Such obstacles include foreign atoms (solid solution alloys), vacant atomic sites (quench-hardened metals), displaced atoms (irradiation-hardened metals), small precipitates (alloys), and other dislocations (work hardening). A metal such as copper, nickel, aluminium, or austenitic stainless steel, hardened by such obstacles is an almost ideal engineering material. It is hard but when the yield stress is exceeded the dislocations can move very quickly, at almost the speed of sound in the material, and so deform the material as fast as the applied forces require. This yield is a very reliable quantity and is not much altered by either

temperature or speed of loading (except at very high temperatures). There is in such a material a vast reserve of plastic deformation to absorb the energy of sudden shocks—e.g. hammer blows—and protect the material against fracture.

Not all materials, even metals, possess this property of "buffering" excessive mechanical shocks. Ordinary steel is a borderline case. The dislocations will not always run rapidly in steel, except at extremely high stresses, and this makes the metal brittle at low temperatures and also at or near room temperature under impact loads. This cold-brittleness and impact-brittleness of structural steel is of immense practical importance. Many bridges and ships have been destroyed by it. Crystals which become hard and brittle at low temperatures do so because their dislocations have an atomic structure with mechanical properties more like those of glass than those of soft metals. We might say that the dislocations in soft metals have "soft centres" whereas those in intrinsically hard and brittle crystals have "hard centres" which, like glass, become soft only at high temperatures. This is proved by deforming, for example, a silicon crystal at high temperatures, to put dislocations in it, and then deforming it again at room temperature. In spite of these dislocations it remains hard and brittle at room temperature; these dislocations have become "frozen up" in their positions at room temperature.

There is an important lesson in this. Great attempts are constantly made to increase the strengths of metals and alloys by alloying, heat-treating, and working, these materials. What is the ultimate limit to this development? What we are doing in effect is freezing up the dislocations by introducing more and more effective obstacles to them. In the end then we shall simply make these materials brittle! In fact this can already be done by making metals and alloys, e.g. intermetallic compounds such as $CuAl_2$, with complex crystal structures in which dislocations are unable to move. These are perfectly metallic materials but are brittle. They bring us round in full circle back to the problem of glass again. If we make metals glass-hard they are likely also to be glass-brittle!

The primary metallurgical problem therefore is not one of pushing on and on with processes of increased hardening, but of combining hardness with crack-resistance. We may accept some

loss of hardness by building the hard constituents into a softer matrix, as in tungsten carbide tools in which the hard tungsten carbide grains are cemented together by cobalt. Alternatively we may try to develop fibrous structures in which the brittleness that goes with extreme hardness can be accepted without a loss of crack-resistance.

Ductile fracture

Ductile materials do break of course and there is a lot of interest at present in the way that they do it. Sometimes the process is extremely simple, and is no more than a form of necking. Ideally a neck should continue until the cross-section is reduced completely to a point or a knife-edge. This is occasionally observed although more commonly the material breaks well before this stage is reached. Careful examination of such fractures has shown that they usually occur by a process of "internal necking". If there is a small cavity in the material, e.g. an initial hole or a place where the metal has pulled away from the surface of a foreign inclusion, this cavity can expand plastically under the forces exerted in the necked region, by a process which is essentially the same as the inward growth of the external neck. When several such cavities grow simultaneously they eventually link up to form a complete fracture. While this is certainly not the whole story of ductile fracture—there is also an important process of shear fracture which is not properly understood as yet—nevertheless it is a common form of such fracture. It is of great practical importance because it seems also to be the mode by which metals and alloys break along grain boundaries under high-temperature creep and fatigue conditions; although here the deformation is caused not so much by dislocations as by diffusion and viscous movements in the neighbourhood of the grain boundaries.

Fatigue failure is the major mode of fracture in ductile materials during service under oscillating stresses at ordinary temperatures, and its importance in engineering can hardly be overemphasised. It is undoubtedly the most complex of all the various modes of failure and we are still some way from understanding it. Some things have recently become clear however and it is now possible to give a fairly full description of the development of a

fatigue failure, even though the various stages involved are not yet all understood. The oscillating stresses produce slip bands which can be seen on a well-prepared surface of the specimen. After a number of oscillations some of these slip bands become thick and prominent in appearance, as if a large amount of slip were taking place on them, and various pieces of evidence suggest that the material in these particular bands has become soft. This is the first stage in fatigue failure; it appears to be a failure in the work hardening process, amounting in some cases to a work-softening of the material, on certain slip bands after many oscillations of stress. This failure of work hardening has the result that large plastic strains then occur on these softened bands during each successive cycle of the applied forces, and these large plastic strains gradually induce a more radical failure of the material. Where the soft slip bands meet the free surface of the specimen some of the material in them is gradually extruded out in the form of a thin ribbon; correspondingly, fissures are formed, running into the specimen along the softened bands and on one side of the extrusion. These fissures gradually spread down the soft slip bands and become fatigue cracks.

Various atomic mechanisms have been suggested to explain the formation of the extrusions and fissures. It begins now to look, in some cases at least, as if the process may be quite simple; no more in fact than the mechanical squeezing out of the soft sandwich material during the compressive phase of the cycle, the harder material on either side serving as anvils. We have recently made a simple experiment in Cambridge to test this idea. We joined two copper cylinders together, end-to-end, by a layer of lead-tin solder and then fatigued this composite specimen in a push-pull apparatus. The solder squeezed out of the joint in much the same way as the softened slip band material does in ordinary fatigue specimens, and in this case it is obviously a simple mechanical extrusion of a soft layer between two hard blocks. We have also produced the effect on lamellar eutectic alloys; plates of soft metal, sandwiched between plates of hard metal, are extruded out during fatigue.

There is a great deal of work still to be done, but already we can see some things of practical importance. The recognition that it is the oscillating plastic strain that does the damage enables us

to understand why work hardening and surface hardening are so important and why the fatigue strength correlates well with the ultimate tensile strength of the material. We also now recognise the importance of work softening and the danger of not having a large reserve of work hardening capacity in the material. While we do not entirely understand the general atomic processes that lead to the soft state in certain slip bands, nevertheless we can see quite easily what may happen in particular cases. If, for example, we have efficiently heat-treated an aluminium alloy to its state of maximum hardness, then the further structural changes which are subsequently produced in that alloy, for example the redistribution of the alloying atoms produced by the oscillating plastic strains in the slip bands, may be expected to lead to softer states and thus to soft slip bands. There is no doubt that this happens in some hard aluminium alloys and that this is partly the reason for some of the fatigue troubles of such alloys in aircraft.

In conclusion, we see what an interesting subject is the strength of solids. It presents a unique opportunity for atomic science to contribute to general engineering, allowing us to try to solve practical problems of great importance by studying the atoms of the material and what they are doing. This intimate combination of atomic science and practical engineering is enormously stimulating and satisfying to those who work in this field.

EXHIBITS IN THE LIBRARY

(*a*) A display of specimens and photographs illustrating various kinds of fracture in metals, alloys, plastics and wood and fatigue in metals, lent by the *Royal Aircraft Establishment, Farnborough.*

(*b*) Photographs of dislocations in metals, lent by *Professor A. H. Cottrell.*

FIRE RESEARCH

By S. H. CLARKE, C.B.E., M.Sc.
Director, Warren Spring Laboratory, D.S.I.R.

Weekly Evening Meeting, Friday 21st October, 1960

W. E. Schall, B.Sc., F.Inst.P.
Treasurer and Vice-President, in the Chair

In his Presidential Address to the British Association, Sir George Thomson described two aspects of science: it is useful in making possible the control of natural processes, and it brings increased understanding of a pattern with an intrinsic beauty as compelling as that of any art, and worthy of study in its own right. Both aspects are apparent in fire research, an applied science in which all the disciplines are marshalled to reduce the hazard to life and property by fire.

Like science, fire has two aspects: it is proverbially a good servant, but a bad master. In the latter role it can be a social problem of some magnitude. Last year fire brigades attended 240,000 fires in the United Kingdom and the damage was estimated at £44,000,000. 445 people lost their lives. Figures for injuries are not yet available, but in an average day some 500 patients are in hospital as a result of burns. These were only the direct effects; it has not been possible to assess the many indirect ones, which may be as great.

Many of the fires and much of the damage could have been prevented by the application of existing knowledge. Nevertheless, the largest fire of modern times—perhaps the largest single fire of all time—occurred a few years ago in a modern building which had been assessed by experts as fire-resisting. One of the main aims of fire research is to protect against the hazard of future fires in a rapidly advancing industrial world which makes ever new and ever greater demands.

While there is little point in speculating on the precise moment of history at which research in fire protection began, it was at a very early stage that experience taught the first lesson of fire protection—the necessity of controlling what is still a major source of ignition, namely the domestic fire.

The continuous systematic study of fire started in Europe and the United States in the closing years of the last century. Added

impetus came with the war, and modern fire research owes much to the vision of the late Sir Reginald Stradling then Chief Scientific Adviser to the Ministry of Home Security, the wartime leadership of The Rt. Hon. The Viscount Falmouth, then Head of the Fire Research Division, and to the knowledge and experience of Professors G. I. Finch and D.T. A.Townend. Finch brought exceptional vigour and suggested many critical experiments which were of great value in elucidating some of the more important basic phenomena. He showed that although many of the problems of fire protection were extremely complicated, they were in fact the result of an intricate pattern built on relatively simple principles.

For a fire to occur there must be fuel, oxygen, and a source of ignition. This is a slight oversimplification, and there are exceptions, but they are of almost negligible practical importance.

It is helpful to approach the study of fire by examining a shallow dish of petrol—a volatile, flammable liquid. As the vapour escapes into the air, concentration is high near the surface of the liquid, and diminishes as the distance from the surface increases. If a small flame is gradually brought near to the surface, the vapour ignites when the flame is perhaps an inch from the liquid; the eye can just follow the rapid spread of flame. Incidentally a cigarette can be extinguished by gently dipping the lighted end into a tray of petrol.

If the experiment is repeated with a tray of paraffin (kerosene) it will be found that quite a large flame must be played directly onto the surface for some little time before ignition takes place. Once ignition occurs, however, and the flames have warmed the liquid, if they are snuffed out by placing a board over the tray, immediate reignition occurs when the flame approaches the surface, exactly as with the petrol.

It is thus necessary to distinguish two temperatures: first the "flashpoint", which is the temperature at which vapour distills rapidly enough to support a flame; and secondly the "ignition temperature"—and this is usually a higher one—at which the flammable vapours can be ignited.

It should be noted that combustion occurs in the vapour phase, and in a region where there are convenient proportions of vapour and oxygen. The chemical reaction which takes place

A. Specimen of wood igniting after subjection to high intensity heat radiation.
(*Crown copyright reserved*)

B. Successive stages in the ignition of wood by radiation. Pictures taken at about 1/100 sec. exposure. Note ignition occurs above the specimen outside the radiation field.

PLATE I

between the fuel vapour and the oxygen liberates heat which may itself be the igniting source which continues the fire. Fire research consists largely in tracing the pattern of this heat, measuring its temperature in a wide variety of conditions, and observing its effect on innumerable materials and on structures.

A great deal of research has been carried out to improve methods of measuring temperature, and scores of ingenious devices have been produced—not all directly for fire research but they have been used in its aid.

Ignition temperatures may vary. There are, for example, many substances which act as catalysts, and if small quantities are present, some chemical reactions take place at lower temperatures than normal. Again some substances, and ether is an example, can undergo a type of partial burning at a relatively low temperature, with what are known as "cool flames". Interesting pioneer work in this field was carried out by Professor D. T. A. Townend and his colleagues. Until these phenomena were elucidated certain mysterious outbreaks of fire were not understood: for instance fires in hospitals which occurred when a blanket was pulled from a patient.

Although the chemical processes that are involved when wood is burned are much more complicated, in some ways wood and other similar materials may be thought of as behaving like liquids with a high flash point. When wood is heated it decomposes, and gases and vapours are formed which, in contact with air, behave just like those of petrol or paraffin, and burn with flame.

G. I. Finch summarised very neatly the behaviour of wood as a fuel. He found it convenient to classify combustible materials in three grades which he called "tinder", "kindling" and "bulk fuel". Tinder can be ignited by an ordinary match and is then able to continue burning; it has a specific surface of not less than 20 cm ^{2}/g; paper or wood shavings are an example. Kindling cannot be ignited by a match but can by tinder, and if it is suitably arranged can continue to burn; it has a specific surface of not less than 2 cm ^{2}/g. Bulk fuel can only be ignited by a fire which already involves kindling, but under suitable conditions it can sustain self-combustion; its specific surface is less than 2 cm^2/g.

It is simple to demonstrate that a sheet of paper can be ignited with a match, and will continue to burn, whereas a thick piece of wood will not do so. As Finch pointed out the reason is that heat from the burning wood is being dissipated by radiation from the flames, and by conduction with the interior of the wood, and if too much is lost destructive distillation ceases and the flames die out. If the wood is thin enough heat conducted from one side is counterbalanced by heat from the other, and burning continues; in practice wood of less than about $\frac{1}{4}$ or $\frac{3}{8}$ inch (depending on density, and on dryness) will continue to burn when ignited.

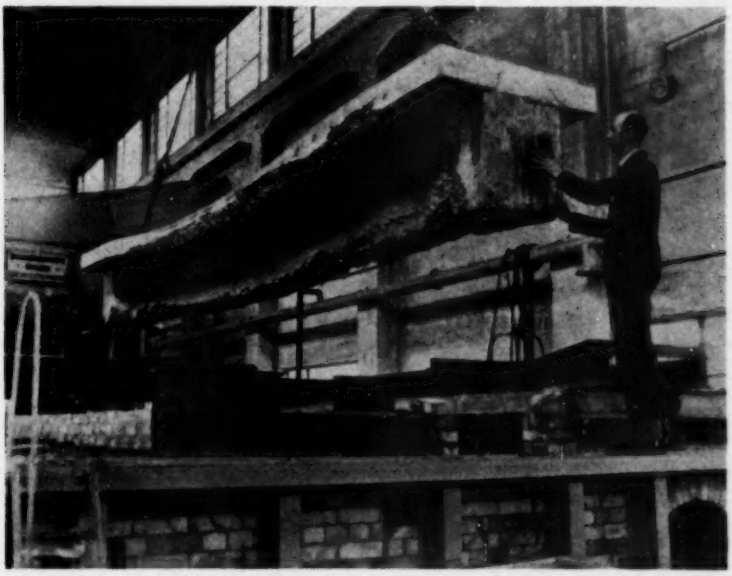
Similarly, heat lost by radiation may be counterbalanced by supporting heat from a neighbouring fire. Large pieces of wood of any size will burn to destruction if they are near enough, say, $\frac{1}{2}$ inch or less apart, and a fire is started between them.

D. I. Lawson, the present Director of Fire Research, and P. H. Thomas observed an interesting feature in the burning of wood. When small specimens are subjected to radiant heat of high intensity, vapours and gases are emitted which ignite spontaneously. The interesting thing is that ignition occurs not at the point of applied heat, but some distance above, and the flame jumps rapidly back to the wood (Plate IA and B).

The processes described form the background to the early stages of most fires. Once started, a fire spreads until all the exposed surface of combustible material is involved in flame. At that moment the maximum temperature is reached. The rate at which it is reached depends largely on the amount and arrangement of the combustible materials. When it is reached subsequent developments depend largely on the access of air to the fire. Approximately half the mass of the wood is lost in flame, and the other half glows as charcoal.

It has already been noted that the first practical fire precaution is the control of possible sources of ignition. The second is the control of the amount of combustible material that can be involved at one time. The problem of dealing efficiently with the large quantities of materials that have to be handled and stored in the modern world is extremely difficult, and a substantial proportion of the effort in fire research is aimed at its solution. Frequently it involves the division of large buildings into com-

A. Collapse of unprotected steel in fire. (*By courtesy of the Fire Chief Officer, London Fire Brigade*).



B. Pre-stressed concrete beam after fire resistance test. (*Crown copyright reserved*).

PLATE II

partments each of which has a pre-determined degree of fire resistance.

Observations made at many large fires and in experiments have led to the almost universal acceptance of a standard time-temperature curve (Fig. 1) which is considered to represent the development of temperature in a severe fire. "Fire resistance" is defined as the length of time for which a unit of structure continues to perform its design function when it is heated in a furnace which is controlled according to the standard curve. By-laws in most countries now require buildings in towns to be constructed so that their walls, floors, structural columns, and certain doors and windows reach an appropriate degree of fire-resistance. Steel columns have a fire resistance of about ten minutes and the problem is, therefore, to provide them with a heat-resisting coating which will stay in position (Plate IIA).

It sometimes comes as a surprise to find that steel behaves so badly in fire; but it may be a greater one to learn that a number of fires have been caused by the combustion of fine steel wool, which is readily ignited by a match, or even by allowing a handful to fall across the terminals of a small battery; and there have been many fires in the steel tubes of boilers in which overheated tubes have burned in high pressure steam.

The variety of possibilities in constructing fire-resistant buildings is so great, and the present state of our knowledge so small, that full-scale tests are often necessary before approval can be given for the use of a new form of building construction. Furnaces were built by the Fire Offices Committee nearly thirty years ago to enable such tests to be carried out and they were made available to the Building Research Station of the Department of Scientific and Industrial Research for research purposes. When the Joint Fire Research Organisation was set up in 1947 they formed part of the contribution of the Fire Offices Committee to this Organisation.

Plate IIB shows one specimen after test, and gives an idea of the size of the operation. Such tests are costly and time consuming, and much research has been designed to find means of eliminating them, or at least of conducting them on a smaller scale. The research involved the search for mathematical expressions for the variations in temperature in every part of a wall,

floor, column etc., when the temperature of the surface is raised at the rate demanded by the standard time-temperature curve.

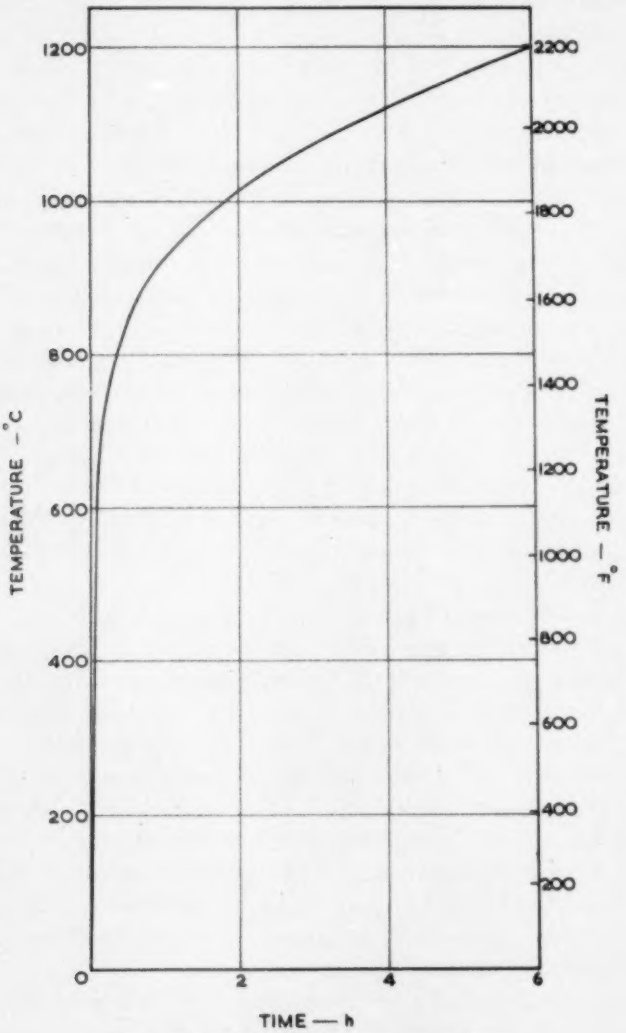


FIG. 1 Standard Time-Temperature Curve.
(British Standard 476)

Bearing in mind that, to take a simple example, a steel girder may be protected by an air-gap between itself and a slab of

building material which may range from chipboard to lightweight concrete using exfoliated vermiculite as an aggregate, with a coat of plaster, even when the thermal constants of the individual layers are known the calculation of temperature rise in the steel is a difficult and tedious operation. Lawson and McGuire devised and constructed an electrical analogue which has proved extremely valuable both as a research tool, and in reducing the number of full scale tests. It exploits the close analogy which exists between the flow of heat in solids and the flow of a charge along a transmission line composed of series resistance and shunt capacitance elements.

The analogue deals with one scientific problem, namely the behaviour of units of building construction under closely defined conditions. There remain a wide range of problems resulting from the movement of hot gases and the transfer of heat, such as the provision of escape facilities in high buildings, the control of smoke in large basements or in ships, the "mushrooming" of hot gases in buildings of large area, the detection of fire, and many aspects of extinction. Before these can be studied on a small scale there is need of a reliable technique for the use of models. Considerable progress in this direction has been made by P. H. Thomas and C. T. Webster. Working with similar cubical models from 1 ft. to 10 ft. side, they have studied the burning of wooden cribs of various sizes, and have established relationships that have already enabled them to deal with some practical situations.

It has long been recognised that smoke is perhaps the fireman's greatest enemy. It offers particular difficulties in buildings with a large expanse of floor area with all kinds of obstructions which together make it impossible for the fireman to see or to find his way to the seat of the fire. The Covent Garden fire and several other recent large fires in this country have focused attention sharply on this problem. They have led to a revived interest in a method of fire protection that has been employed in theatres for many years, namely the provision of emergency venting in the roofs to release the smoke and hot gases at an early stage in the fire. P. H. Thomas has recently developed for the first time what appears to be a satisfactory solution with an adequate theoretical basis. Using models, he has explored the combined

use of "curtains" to restrict the lateral spread of smoke in conjunction with roof vents of various sizes, and has established a relation between vent area and the proportion of heat released in experimental conditions.

Detection

Experience of large fires soon convinces that when they get beyond a certain size, total destruction is inescapable. A surprisingly large proportion of the total damage is caused by a relatively small number of large fires; each year nearly half the damage is caused by some 200-300 out of some 50,000 fires in buildings attended by the fire brigades. Of the many factors that contribute to the development of large fires the most important is failure to detect and attack them while they are still small. P. Nash and R. Pickard have explored the rise in temperature and the movement of hot gases over fires of various sizes in enclosures of various heights and shapes, a task which called for entirely new instruments for measuring air-flow. Using the results of this work, together with information about the distance of travel of fire brigades and experience of the desirable balance between high sensitivity and the likelihood of false alarms, they have succeeded in developing a standard procedure which enables the merits of new designs of detector to be assessed.

Before leaving the subject of the occurrence of fires, reference should be made to the fact that effective statistics are collected by the Fire Brigades of the Local Authorities by arrangement with the Home Office. These have yielded a number of interesting results, including indications of significant differences in behaviour of pre-war and post-war houses and pre-fabs—the post-war housing having the best record. They have revealed a steady increase in fires associated with electrical equipment, and with the use of certain types of oil-burning apparatus.

Extinction

When attempts to control sources of ignition and accumulations of fuel have failed, there remains the task of fire extinction. The most common method is to cool the fuel to a temperature at which the flammable vapours cease to be emitted.

The commonest extinguishing agent is water, and the princi-

ples that govern its use have not changed fundamentally over hundreds of years. Whenever it can be used it is incomparably

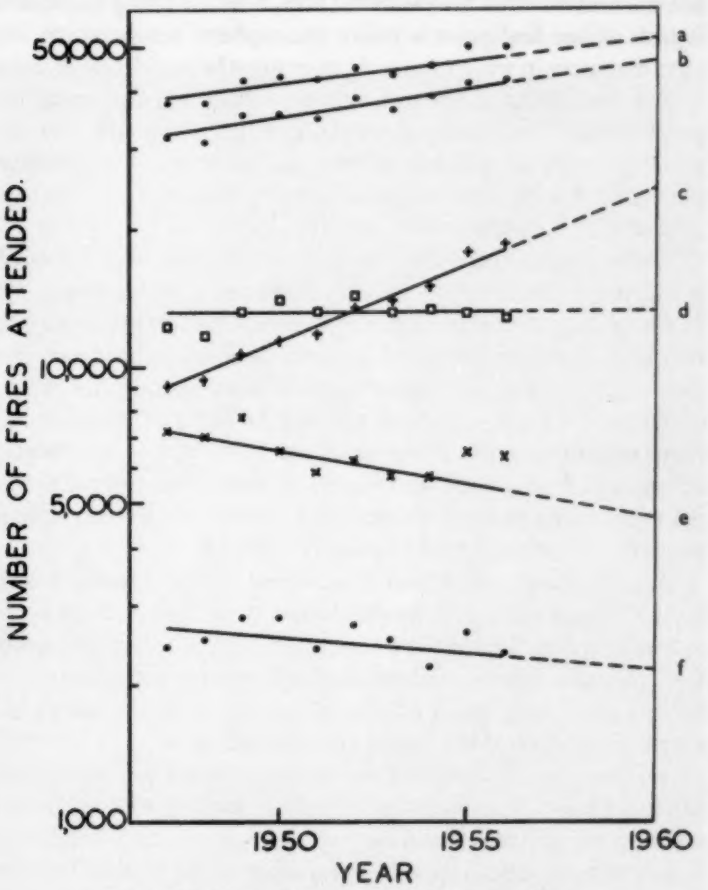


FIG. 2 Methods of extinguishing fires in buildings.

(*a*) Total fires in buildings. (*b*) Total fires in buildings extinguished by Fire Brigades. (*c*) Fires extinguished by Fire Brigades using hose reel jets and water in tank. (*d*) Fires extinguished by Fire Brigades, methods not specified. (*e*) Fires extinguished by Fire Brigades using jets from Council hydrants. (*f*) Fires extinguished by Fire Brigades using hose reel jets and more water than that in tank.

the best medium; it might have been designed for the purpose. There is plenty of it and it is cheap; it is easily transported (by pipes) and easily applied. It has a large thermal capacity and it

boils at a convenient temperature absorbing a useful amount of heat in doing so. The only circumstances in which plain water is not the best medium are electrical fires, fires involving flammable liquids whose flashpoint is below atmospheric temperature, and circumstances in which water damage must be avoided at all costs.

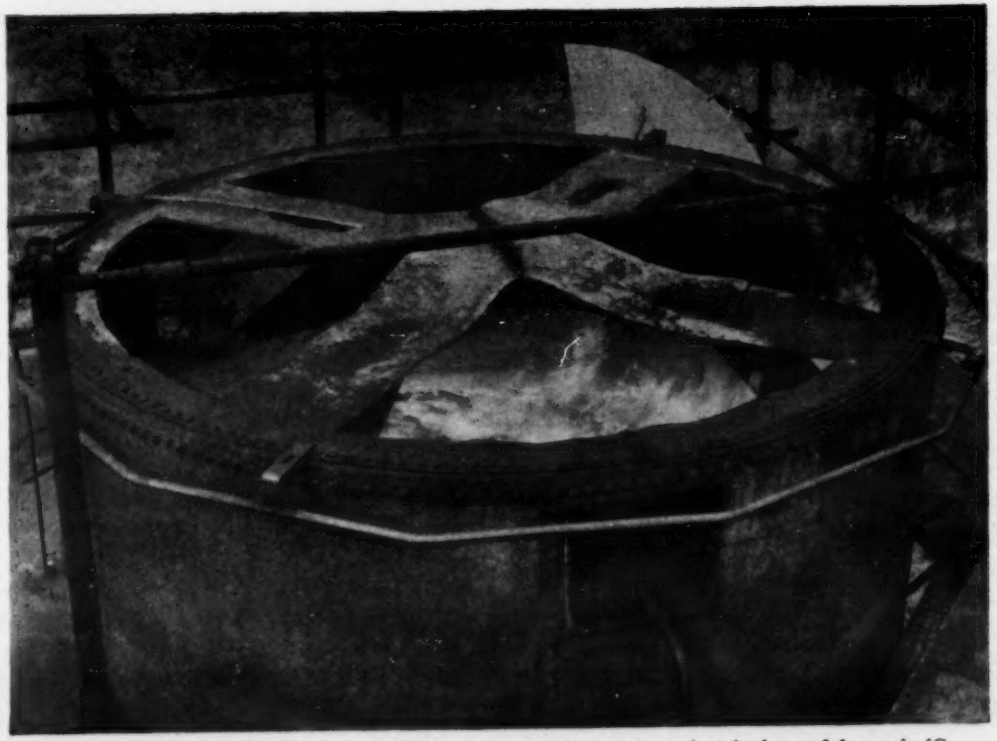
The main lines of research in recent years have aimed at improvements in methods of applying water. Since the war improvements in equipment, training and technique have resulted in a marked and continued steady improvement in the effectiveness of Fire Brigades in this country (Figure 2).

It was appreciated during the last century that where possible it was more effective and economical to apply water as a spray. In the early post-war years the opinion was held in some quarters that high-pressure sprays, which were believed to have very fine drops, represented the ultimate in efficiency. A long and careful study by D. Hird, in which the fire brigades in London and Birmingham took part, demonstrated that there is no material advantage in increasing operational pressure above about 100 lb. per square inch and any theoretical merit fine drops may have in extinction is offset by their limited trajectory.

D. J. Rasbash has shown that, where water is used, fires in liquids which cannot be cooled below their flashpoint must be extinguished in the vapour phase by the use of a very fine spray. Less volatile liquids such as fuel oil can be extinguished by cooling and larger drops which will pass through the flames and reach the surface of the liquid are more effective.

Another way of using water is as foam, which is made by dissolving a foaming agent (often a protein derivative) in water and aerating the solution mechanically or by producing bubbles of carbon dioxide chemically. The function of the foam is to cover the surface of the liquid and to shield it against radiant heat from the fire, thus cutting off the supply of flammable vapour.

One of the most interesting results of recent research has been the establishment of the best types of foam for certain special purposes. During the war it was found possible to introduce foam at the base of a tank of fuel oil and to let it rise by its low, relative density and spread over the surface of the oil (Plate III). This was not possible with petrol, because in ascending through the bulk of the liquid the foam became impregnated with petrol



Extinction of fire in petrol tank, 30 ft. high, by foam which was injected at the base of the tank. (*Crown copyright reserved*).

PLATE III

which continued to burn and destroyed the foam. Studies in the Laboratory, which were confirmed on a large scale, revealed the surprising conclusion that very sloppy foams, with an expansion of about three times, could be used satisfactorily even with petrol.

There are two other types of media that can be used for special fires. The first are known as vaporizing liquids, the commonest being carbon tetrachloride. They operate in the vapour phase by absorbing heat, and possibly also by inhibiting the combustion reactions. Research has been devoted to seeking to understand the mechanism of the reactions, and to selecting the most effective of a wide range of reagents. In recent years chlorobromomethane has come to be regarded as the best of the available materials. When weighing the merits of various agents, the toxicity of the agent, or its decomposition products, has to be considered.

D. J. Rasbash recently made the bold suggestion that the principle of controlling the atmosphere might be used on the grand scale even for such fires as that at Covent Garden. A large jet engine was specially modified by the National Gas Turbine Establishment, and the exhaust gases from this engine are being used experimentally in a large building to see how far practical use can be made of the principle. The inert, exhaust gases do not cool the fuel, but it is hoped that they will prevent the spread of combustion long enough for a fireman to be able to approach with his hose.

The other type of medium is known as "dry-powder", usually in the form of sodium bicarbonate. Research has not yet fully elucidated its mode of action, but experience has thrown considerable doubt on its superiority over other cheaper, and better-known methods.

Fire as a Social Problem

It was said at the beginning that fire is a social problem. An example will illustrate some of the difficulties in applying the results of research. A few years ago D. I. Lawson and his colleagues studied the occurrence of casualties through the ignition of clothing. Fire brigades and a number of hospitals co-operated by sending reports on a large number of casualties, and in many instances they sent the garments which were involved, or samples

of the ones which were first ignited. The researches involved studies of a large range of fabrics in the laboratory and a simple equipment was developed as a standard measure of their flammability. Statistics showed that nearly a quarter of the fatal casualties were children, and of those a large proportion were wearing nightdresses. Very few occurred between the ages of about 10 and 60, and the vast majority were elderly people, and often old ladies. It was clear that the practical solution was not to aim immediately at the prohibition of all but flame-resistant fabrics; special care of the young and old was called for, and increased attention to the control of sources of ignition such as electric fires, gas fires, and the domestic fire. It was considered important that the public should be informed about the hazards of certain fabrics and that means should be provided for them to be able to recognise the ones which presented the least hazard.

Deliberations of this kind call for wide collaboration. Fire touches practically every aspect of life, and some fourteen Government Departments have special concern in fire protection: the Home Office is responsible for the safety of the public where they assemble in buildings and other places, and for ensuring that the efficiency of the Fire Brigades is maintained: the Ministry of Transport for ships: the Ministry of Aviation for aircraft, and so on. The Fire Research Board gives opportunity for members of industry and of the universities to consider their problems, and with assessors from the Government Departments, to ensure that the research programme is balanced and co-ordinated. The Joint Fire Research Organisation itself is believed to be the only example of an equal partnership of Government (through the Department of Scientific & Industrial Research) and industry (through the Fire Offices Committee) to deal at national level with a social problem.

EXHIBITS IN THE LIBRARY

(*a*) Model temperature and radiation measuring device, mounted diagrams and photographs illustrating aspects and methods of fire research, lent by *The Director, Joint Fire Research Organisation.*

(*b*) Model of a typical warehouse fire, photographs illustrating the work of the London Fire Brigade and possible causes of fire, lent by the *Chief Fire Officer, London Fire Brigade.*

(*c*) Model of a 19th century fire engine, coloured aquatints of historic fires, early books and pictures relating to fires, lent by *The Director, Fire Protection Association.*

VERY FAST CHEMICAL REACTIONS

By G. PORTER, M.A., Sc.D., F.R.S.
Professor of Physical Chemistry in the University of Sheffield

Weekly Evening Meeting, Friday 4th November, 1960

Brigadier H. E. Hopthrow, C.B.E., M.I.Mech.E.
Vice-President in the Chair

THE science of chemistry is concerned with only two things—the structure of substances and how one structure changes into another. By analogy with mechanics we may call these two divisions chemical statics and chemical dynamics.

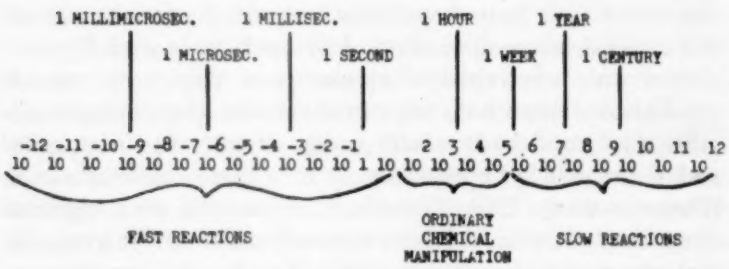
This matchbox represents a mechanical system in metastable equilibrium and this piece of nitrocellulose is an analogous chemical system. A static investigation of these objects would be concerned with their shape, structure and the forces, external and internal, acting upon them. A dynamic study would be concerned with how rapidly they change as they move towards equilibrium. Since both are metastable the changes are negligibly slow until the necessary energy of activation is supplied and then both fall spontaneously to a more stable situation. (*Demonstration*). This discourse is concerned with chemical dynamics, or kinetics as it is more usually called, and in particular with the study of reactions which, like the decomposition of nitrocellulose, occur very rapidly.

The rates and durations of chemical change vary over a wide range as is shown in the first diagram. Reactions whose progress can be followed by conventional methods in the laboratory are limited to the middle part of this range. Very much slower reactions, such as rusting, corrosion and decomposition are, of course, often quite important. Nearly every substance in the chemical laboratory is thermodynamically unstable and is decomposing at a slow but definite rate. All organic matter is thermodynamically unstable and we owe our temporary existence here to the slow rate at which we decompose to water, carbon dioxide and similar more stable but less interesting compounds. Humane considerations, as well as lack of time, prevent me from demonstrating this reaction and I will represent the slow end of our scale with this half-century old bottle of port. The reaction is still proceeding and I am warned that if allowed

to proceed much longer the liquid will be quite undrinkable.

Turning now to the other end of the scale—chemical changes which occur in less than one second—we find a much greater variety of important reactions. Indeed the study of chemical kinetics is almost synonymous with the study of fast reactions because the simplest and most fundamental reactions are usually very fast and most slow reactions proceed by a series of steps many of which are also fast. Let us begin by looking at a few familiar examples.

Ionic reactions are usually so fast they appear instantaneous. The combination of ions to form an insoluble salt (*Demonstration*) and the neutralisation of an acid (*Demonstration*) already provide examples near the extreme fast reaction end of our scale, in fact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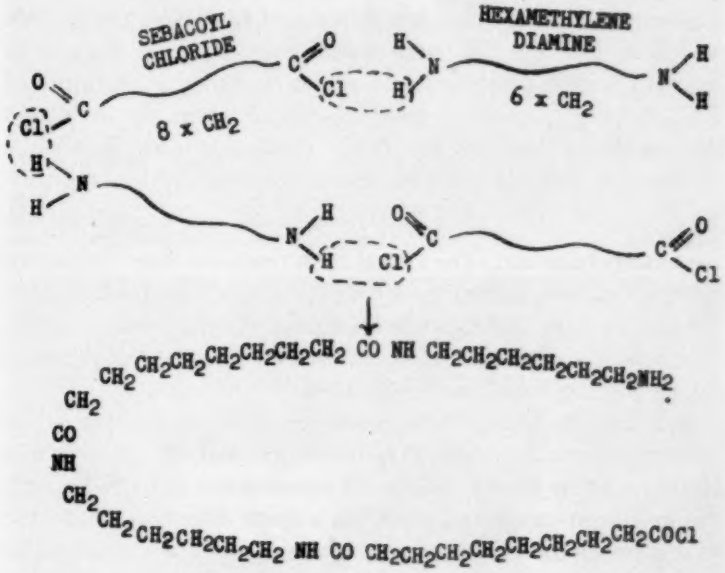
FAST REACTIONS
ORDINARY CHEMICAL MANIPULATION
SLOW REACTIONS

the acid-base reaction, with normal solutions, is nearly complete in 10^{-11} seconds providing mixing is rapid enough. When metals exchange ions to produce an electric current (*Demonstration*) the electrochemical reaction is again nearly instantaneous, indeed it would be inconvenient if we had to wait half an hour for the doorbell to ring.

Organic reactions often proceed more slowly but this is not always the case. Polymerisation, for example, almost invariably involves very rapid reactions. This is clearly illustrated in the reaction between sebacoyl chloride and hexamethylene diamine to form nylon (*Demonstration*). The two solutions do not mix and are immediately isolated from each other by a film of nylon. If I now withdraw this film it will spin nylon for us continuously. The time available for the liquids to react as the film is withdrawn is less than one tenth of a second and in this time a nylon molecule

having a chain of about a hundred molecular units is formed, so that the time for each reaction step must be less than one millisecond (see diagram).



NYLON 68

These are all solution reactions. Gases can react just as quickly, for example ammonia and hydrochloric acid gases form, in a fraction of a second, particles containing a million molecules of ammonium chloride (*Demonstration*). The formation of carbon particles in a flame, involving many complicated steps in the decomposition of an organic fuel occurs equally rapidly (*Demonstration*). In fact the process of combustion is one of the most important and spectacular of all fast reactions but, in view of the comprehensive demonstrations of this phenomenon which will be presented tomorrow evening, I shall refrain from illustrating this point tonight. You may, however, be interested to see one of the newer solid fuels which are being increasingly used for rocket propulsion. This is a plastic propellant, and it consists of a rubbery polymer (polyisobutene) mixed with a solid oxidant such

as ammonium perchlorate. It burns quietly at a rate of 4 mm. per second and, having its own oxidant, it requires no air—you see it burns quite readily under water (*Demonstration*).

Before I describe how the rates of these fast reactions can be studied, it will be useful to review briefly what are the factors which determine the rates of chemical change. All chemical systems have a tendency to move towards equilibrium or lower free energy but the rate of reaction is not determined by the position of equilibrium. Here are two gas mixtures which illustrate the point. This is a mixture of hydrogen and oxygen and, although it is far from being in equilibrium, the rate of reaction is negligible. Here, on the other hand, is a mixture of NO_2 and N_2O_4 which is in equilibrium although the molecules are reacting rapidly all the time. There is no overall change because the forward and back reactions of the equilibrium

$$2NO_2 \rightleftharpoons N_2O_4$$

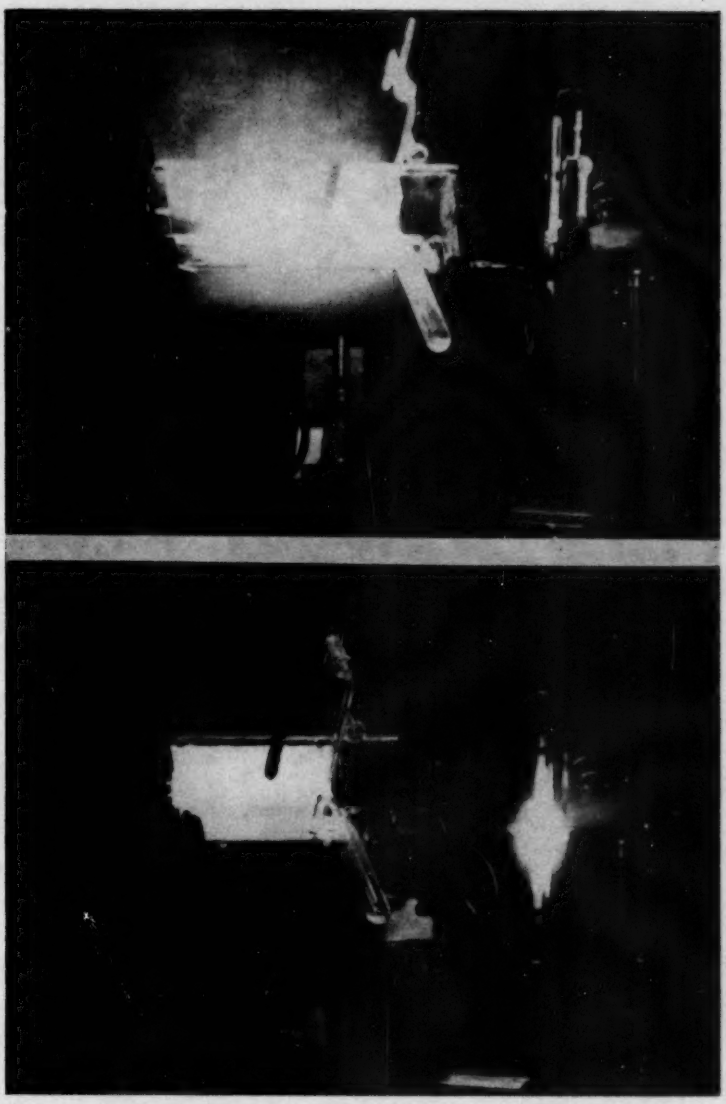
are exactly balanced. The rate of both reactions depends on two factors—the concentration, or gas pressure, and the temperature. We can see how this happens by means of a mechanical model. (*A kinetic model was shown which illustrated dynamic equilibrium in a system of single and double particles*).

If I raise the temperature of this nitrogen dioxide system the colour darkens as more NO_2 is formed and the equilibrium shifts smoothly so as to follow the temperature change. Heating the hydrogen-oxygen mixture has a quite different effect—the heat supplies the energy of activation necessary to initiate rapid reaction and the system returns explosively to equilibrium (*Demonstration*).

Clearly, therefore, to say that a reaction is fast or slow has little meaning unless concentration and temperature are specified. The usual way of doing this is to refer all rates to unit concentrations—this rate is then called the rate constant and it is an easy matter to calculate the rate at any other concentration for the same temperature. To allow for the effect of temperature we use the Arrhenius equation which has been found to apply quite accurately to reactions of many kinds. This important equation is

$$k = A\, e^{-E/RT}$$

where R is the gas constant and T is the absolute temperature.



Photographs showing operation of the flash photolysis apparatus. The upper photograph shows the photolysis flash and the lower photograph shows the spectroscopic recording flash which fires a fraction of a second later.

PLATE I

By measuring the rate constant k at several temperatures the constants A and E can be determined. Once these are known the rate of reaction can be calculated under any conditions. The constant E is the activation energy—the energy barrier which must be surmounted before reaction can occur and A is the rate constant of reaction of molecules which possess the necessary energy for reaction. The energy path of a reaction whose activation energy is not zero is represented by this model. It consists of two troughs, one lower than the other, and the reaction can only occur when the energy to surmount the barrier is available (*Demonstration*).

We may now turn to a consideration of how it is possible to measure the rates of very fast reactions. Suppose, for example, that I want to measure how rapidly sulphite ions react with iodate ions to form molecular iodine. I might mix the solutions and find that the reaction goes apparently instantaneously (*Demonstration*). The obvious thing to do at this stage is to try to slow the reaction down by reducing the concentration or the temperature and, for this particular reaction, conditions can be chosen in this way to give any convenient rate of reaction. For example I have chosen the concentration of these solutions so that the reaction takes ten seconds. (*The solutions were mixed and iodine was precipitated after exactly ten seconds*). The rate is proportional to the concentration of each ion so, if I reduce the concentration of each solution to one half, the reaction time is forty seconds since the rate is halved twice (*Demonstration*).

Before I go any further you may like to know just what is happening in this rather unusual reaction. The reactions which occur when iodate and sulphite ions are mixed are

$$IO_3^- + 3SO_3^- \longrightarrow I^- + 3SO_4^- \qquad (1)$$
$$IO_3^- + 5I^- + 6H^+ \longrightarrow 3I_2 + 3H_2O \qquad (2)$$
$$I_2 + SO_3^- + H_2O \longrightarrow 2I^- + SO_4^- + 2H^+ \qquad (3)$$

No iodine is formed until all the sulphite is used up and then iodine is rapidly precipitated, but iodide ion is being formed all the time as can be shown by adding a little mercuric ion to the solution. You see now that golden mercuric iodide is precipitated during the early part of the reaction and iodine is formed as before when all the sulphite is used up (*Demonstration*).

The rate of reaction can also be controlled by changing the temperature. Having shown you the reaction which takes ten seconds at room temperature I will now follow the current practice in theatrical circles and repeat the performance on ice. You will see that reaction of the same concentrations now takes nearly twice as long (*Demonstration*).

In this way the rates of many reactions can be controlled so as to bring them into a convenient time range and, by measurement over a range of concentrations and temperatures the parameters A and E can be determined so that the rate can be calculated under conditions when the reaction would be too fast to follow.

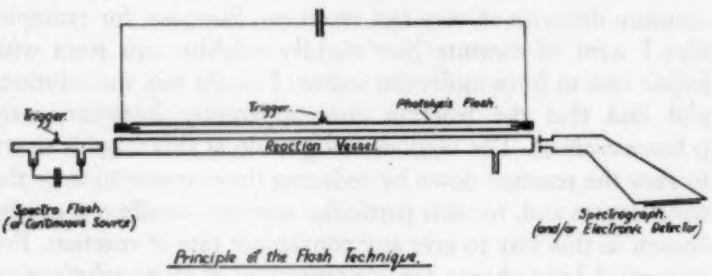


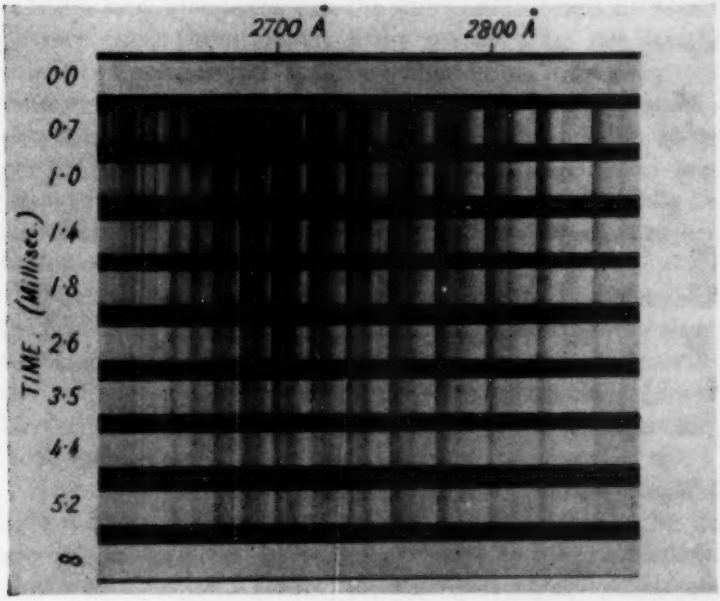
FIG. 1

For example, the times for ethane to be half decomposed into ethylene at various temperatures are as follows:

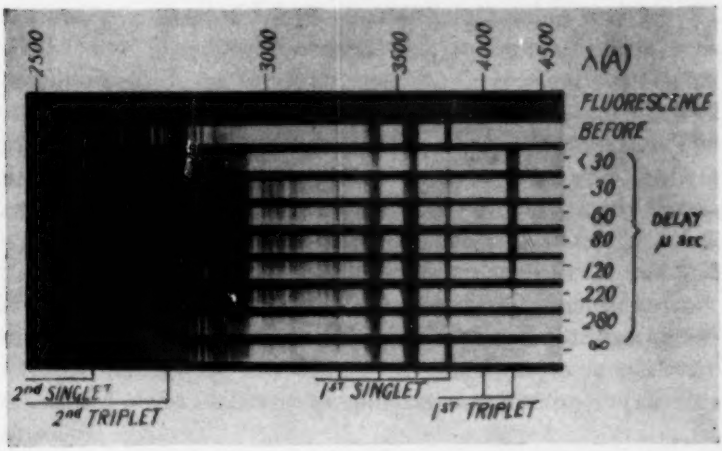
$$C_2H_6 \longrightarrow C_2H_4 + H_2$$

Temperature (°C)	Time for half reaction
20	10^{30} years
300	30,000 years
500	2 weeks
600	5 minutes
700	10 seconds
1000	3 milliseconds
1500	1 microsecond

Nobody has waited thirty thousand years for this reaction to occur nor has anyone followed the change over one millionth of a second, but studies in the convenient temperature range between 500°C and 600°C enable us to predict the rate of reaction when it is too fast or too slow to be measured.



A. Spectra showing the formation and decay of the ClO radical during flash photolysis of a chlorine-oxygen mixture.



B. Spectra showing the formation and decay of the triplet state of anthracene during flash photolysis of an anthracene solution in hexane.

PLATE II

If this were always the case the study of fast reactions would be very easy. Unfortunately many reactions are not greatly affected by temperature and concentration or, if they are, the concentrations necessary to slow the reaction down to a reasonable rate are too low to be measured. Furthermore the whole process of extrapolation from a few minutes to a millionth of a second is a somewhat doubtful procedure and we shall only be completely satisfied when the rate of the fast reaction itself has been measured.

There are two general ways of going about this problem and the first of these gets over the difficulty of measuring very short times by turning the rapidly changing system into one which is stationary in time. At first sight this seems to be a contradiction but the method is well known to anyone who has seen and understood a gas burner.

Here is a tube which I have filled with coal gas and air. If I light it at one end the flame travels rapidly along the tube, its speed being governed by the rate of reaction (*Demonstration*). Now suppose I pump gas into the other end at a rate which just balances the rate of movement of the flame front—the flame will remain stationary and this is just what happens in the ordinary gas burner (*Demonstration*). Here we have a system which is stationary in space although reaction is occurring very rapidly all the time. By physical observations or chemical probes it is possible to study the composition of the flame at various heights and, if we know the rate of gas flow, these measurements lead immediately to the times required for the changes to occur. The times involved in a flame reaction of this kind are very short, a complicated hydrocarbon is converted through many intermediate compounds into carbon dioxide and water in a few thousandths of a second. The exact balancing of flow rate and rate of reaction is very easy in this case because it is self-adjusting; the flame area becomes less if the flow rate is diminished and so reduces the rate of reaction. This phenomenon is perfectly illustrated in the well known exploding can experiment (*Demonstration*).

There are a number of methods for the study of fast reactions which use the same principles and they are therefore called stationary state or flow methods. One of the earliest examples of

this method was the study, by Lord Rayleigh, who was at one time President of this Institution, of the properties of atomic nitrogen. Rayleigh found that when nitrogen gas was pumped rapidly through an electrical discharge, the gas emitted a yellow glow for several seconds (*Demonstration*). He called the species responsible for this "active nitrogen" and suggested that the active species were nitrogen atoms—a suggestion which has subsequently been confirmed. Many gases can be dissociated in this way and the rate of reaction of the atoms and other active species formed is readily determined by making measurements at various points along the tube. If necessary, other substances can be injected into the stream of atoms and their reactions studied. For example air quenches the yellow glow (*Demonstration*) and organic substances react and sometimes give products which themselves radiate—biacetyl gives a green glow for example (*Demonstration*).

One of the most useful applications of flow methods has been to the study of reactions in solution brought about by rapid mixing. Here is a reaction which appears as instaneous as one hopes the ensuing medicinal effect will be (*"liver salts" and water were mixed*) but the reaction between acid and bicarbonate ion which results in the liberation of carbon dioxide

$$HCO_3^- + H^+ \longrightarrow H_2O + CO_2$$

is, in fact, quite slow as ionic reactions go. This can be shown by using a flow method in which acid and bicarbonate are rapidly mixed in the presence of a fluorescent indicator(*Demonstration*). At the point of mixing you see the indicator change from blue to green as the solution becomes acid but the green colour disappears in about one second as the acid is neutralised by the bicarbonate ion. In this way we are observing directly the rate of the above ionic reaction.

Flow methods have the disadvantage that large quantities of material are used and also that, even with the most rapid flow rates, it is usually not possible to deal with reactions which occur in less than one thousandth of a second. The other approach to the study of fast reactions is by what are known as pulse methods. These are relatively new, having become possible only since rapid electronic recording methods were developed, and are potentially the most powerful of all methods of fast reaction study.

Suppose we want to study a reaction which is over in a few millionths of a second. There is no difficulty nowadays in carrying out physical measurements as quickly as this but, if these measurements are to mean anything, we must be able to start the reaction equally quickly and this is the real difficulty. There are really only three ways of bringing about a chemical reaction—by heating, by mixing and by electrical or radiation methods. The three examples of flow techniques which I demonstrated each involved one of these methods and the same three methods can be used to initiate reactions quickly by pulse techniques.

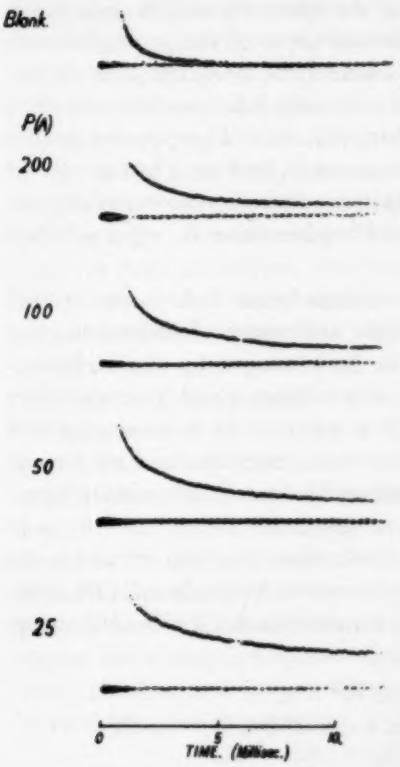


FIG. 2. Oscillographic traces showing the recombination of iodine atoms in argon after flash photolysis of iodine vapour. P(A) is the argon pressure in mm/Hg.

Rapid heating of a gas can be brought about in a few micro-seconds by means of shock waves and equally rapid heating of a liquid by a pulse of electrical current. Mixing is never so rapid, but the "stopped flow technique" which is a very useful modification of the ordinary flow method, makes it possible to mix two liquids and pump them into an observation vessel in about one thousandth of a second.

The third way of bringing about chemical change—by use of radiation—has provided a very powerful method for the rapid initiation of reaction and I should like to say a little more about this method because it is my own particular interest. The method is known as "flash photolysis" and it makes use of two facts;

firstly that it is possible to initiate or modify nearly every kind of reaction by shining light onto the system and secondly that pulses of light of very high energy and short duration can be produced by electronic methods.

The use of a brief flash of light to bring about a chemical reaction has long been familiar to photographers. All substances absorb light in some region of the spectrum and the first result of this absorption is excitation of some of the molecules into states of higher energy. The excited molecules can then do one of several things. If no other processes intervene the absorbed energy will be re-emitted as luminescence. This process usually occurs in about one millimicrosecond (10^{-9} sec.) but in special cases it may be much slower, as in the phosphorescence of organic molecules like fluorescein and triphenylene in rigid solvents (*Demonstration*).

More frequently other processes occur before the excited molecule has time to emit light and many of these processes bring about chemical reaction. In photography the oxidation-reduction reaction is sensitised by a dyestuff and here is another process of this type. This is a solution of ferrous ions and methylene blue. On irradiation the excited dye oxidises ferrous to ferric iron and the dye is reduced to its colourless leuco form. After the flash the reaction is reversed and the system returns to its original state—a so called relaxation reaction in which the position of equilibrium is only temporarily displaced. (*The solution was irradiated with a flash, became bleached and the blue colour returned after about ten seconds*).

dye D + light $\longrightarrow$ excited dye D^*

$D^* + 2Fe^{++} \longrightarrow$ colourless reduced dye $D^{--} + 2Fe^{+++}$

$D^{--} + 2Fe^{+++} \longrightarrow D + 2Fe^{++}$

Most reactions proceed by way of transient intermediates which can only be observed by special methods of this kind. Here is a reaction in which the free radical intermediate lasts just long enough to be seen visually—the reaction between benzophenone and alcohol. This proceeds as follows:

$$(C_6H_5)_2CO + \text{light} \longrightarrow (C_6H_5)_2CO^*$$

$$(C_6H_5)_2CO^* + RH(\text{alcohol}) \longrightarrow (C_6H_5)_2\dot{C}OH + R$$

$$2(C_6H_5)_2\dot{C}OH \longrightarrow (C_6H_5)_2COH.COH(C_6H_5)_2$$

The final product is a white precipitate of benzpinacol but the intermediate ketyl radical, which is blue, can be observed for a second or two after the flash (*Demonstration*).

These last two demonstrations illustrate the principle of flash photolysis quite well. A flash of light is used to bring about an unstable condition in a very short time and the ensuing fast reaction is followed by observing the colour change—or more generally by spectroscopic measurements.

The flash lamps which I have used for these demonstrations have been chemical flashes involving the rapid burning of a metal such as magnesium. They are of rather long duration, one hundredth of a second or more, and are therefore not suitable for the study of very fast reactions. Electronic flashes provide much greater intensities and this lamp, which is typical of those used for flash photolysis, dissipates one thousand Joules in six microseconds and therefore has a power, during the flash of several hundred megawatts—equal to that of a sizeable power station. Here is a smaller flash of very short duration—it lasts approximately forty millimicroseconds (4×10^{-8} sec.).

One way of studying the reaction brought about by the flash is to use a second flash to record the absorption spectrum of the rapidly changing system. The general arrangement is shown in Figure 1 and in the photographs of Plate I. The second flash is timed to fire after a certain delay and a series of spectra at different delays then show the whole course of reaction. Typical records of this kind are shown in Plate IIA and B. The first shows the absorption spectrum of the ClO free radical formed when chlorine and oxygen are irradiated and is the first record to be obtained of this spectrum. The reaction is a very simple one

$$Cl_2 + \text{light} \longrightarrow 2Cl$$
$$2Cl + O_2 \longrightarrow 2ClO$$
$$2ClO \longrightarrow Cl_2 + O_2$$

Plate IIB shows another important type of short-lived intermediate—the excited state. This particular example is the triplet state of anthracene formed by irradiation of a solution of anthracene.

Such records give information about the rates and mechanisms of fast reactions but it is usually more convenient to carry out kinetic studies by photoelectric methods, displaying the

change in light absorption on an oscilloscope. Traces of this kind showing the recombination of iodine atoms in the gas phase, are illustrated in Figure 2.

A wide variety of fast reactions has already been studied by flash photolysis—atom and radical recombination, acid-base and other ionic reactions, free radical reactions, the photochemical reactions of dyestuffs, including fading and phototendering (*an example of phototendering and of the flash photolysis of an anthraquinone dye were demonstrated*), photosynthesis and many others. In addition flash photolysis has been used to initiate combustion and to study the processes occurring during explosion. This mixture of hydrogen and chlorine is the simplest example of such a reaction (*Demonstration*) and was the first known example of a chain reaction. The chain is carried by H and Cl atoms as follows:

$$Cl_2 + \text{light} \longrightarrow 2Cl$$
$$Cl + H_2 \longrightarrow H + HCl$$
$$H + Cl_2 \longrightarrow Cl + HCl$$

Much more complicated explosions have been investigated recently including such technologically important reactions as hydrocarbon combustion, the mechanism of carbon formation and the action of antiknocks. Other examples of flash photolysis work have been laid out in the Library.

In conclusion here are three flash photographs which may appear to have little relevance to fast chemical reactions—all showing animals in rapid motion. But the energy for muscular contraction is stored in chemical form and somehow the chemical reactions must keep up the energy supply. The humming bird beats its wings three hundred times a second and some species of insect such as the midge (Aëdes) hold the record with over one thousand beats per second. How energy is converted from chemical potential energy into useful work in this short interval of time is one of the most fascinating unsolved problems of chemical kinetics.

EXHIBITS IN THE LIBRARY

(*a*) Electronic flash tubes and pictures illustrating methods used in flash photolysis and photographs of spectra, arranged by *Professor G. Porter*.

(*b*) A selection of photographs of explosions, lent by *The I.C.I., Ltd.*

(*c*) Pictures, prints and handbills of historic firework displays, lent by *The Librarian, Guildhall Library*.

FROM THE PROCEEDINGS OF 1860

This historic discourse, which was delivered shortly before the famous debate on evolution between T. H. Huxley and Samuel Wilberforce at the British Association Meeting at Oxford in June 1860, marks the beginning of Huxley's long and successful effort to secure a fair trial for Darwin's theory.

T. H. Huxley was Fullerian Professor of Physiology at the Royal Institution from 1855-1858 and again from 1865-1868. He delivered 22 Friday Evening Discourses, between 1852 and 1883.

WEEKLY EVENING MEETING

Friday, February 10, 1860

SIR HENRY HOLLAND, BART. M.D., F.R.S.

Vice-President, in the Chair

PROFESSOR T. H. HUXLEY, F.R.S.

On Species and Races, and their Origin

THE speaker opened his discourse by stating that its object was to place the fundamental propositions of Mr. Darwin's work "On the Origin of Species by Natural Selection," in a clear light, and to consider whether, as the question at present stands, the evidence adduced in their favour is, or is not, conclusive.

After some preliminary remarks, in the course of which the speaker expressed his obligations for the liberality with which Mr. Darwin had allowed him to have access to a large portion of the MSS. of his forthcoming work, the phenomena of species in general were considered—the Horse being taken as a familiar example. The distinctions between this and other closely allied species, such as the Asses and Zebras, were considered, and they were shown to be of two kinds, structural or morphological, and functional or physiological. Under the former head were ranged the callosities on the inner side of the fore and hind limbs of the Horse—its bushy tail, its peculiar larynx, its short ears, and broad hoofs: under the latter head, the fact, that the offspring of the horse with any of the allied species is a hybrid, incapable of propagation with another mule, was particularly mentioned.

Leaving open the question whether the physiological distinction just mentioned is, or is not, a universal character of species, it is

indubitable that it obtains between many species, and therefore has to be accounted for by any theory of their origin.

The species *Equus caballus*, thus separated from all others, is the centre round which a number of other remarkable phenomena are grouped. It is intimately allied in structure with three other members of the existing creation, the Hyrax, the Tapir, and the Rhinoceros; and less strait, though still definite bonds of union connect it with every living thing. Going back in time, the Horse can be traced into the Pliocene formation, and perhaps it existed earlier still; but in the newer Miocene of Germany it is replaced by the *Hippotherium*, an animal very like a true *Equus*, but having the two rudimental toes in each foot developed, though small. Further back in time, in the Eocene rocks, neither *Equus* nor *Hippotherium* have been met with, nor *Rhinoceros*, *Tapirus*, or *Hyrax*; but instead of them, a singular animal, the *Palaeotherium*, which exhibits certain points of resemblance with each of the four existing genera, is found. The speaker pointed out that these resemblances did not justify us in considering the *Palaeotherium* as a more generalized type, any more than the resemblance of a father to his four sons justifies us in considering him as of a more generalized type than theirs.

The geographical distribution of the *Equidae* was next considered; and the anomalies and difficulties it offers were pointed out; and lastly the variations which horses offer in their feral and their domesticated condition, were discussed.

The questions thus shown to be connected with the species Horse, are offered by all species whatever; and the next point of the discourse was the consideration of the general character of the problem of the origin of species of which they form a part, and the necessary conditions of its solution.

So far as the logic of the matter goes, it was proved that this problem is of exactly the same character as multitudes of other physical problems, such as the origin of glaciers, or the origin of strata of marble; and a complete solution of it involves—1. The experimental determination of the conditions under which bodies having the characters of species are producible; 2. The proof that such conditions are actually operative in nature.

Any doctrine of the origin of species which satisfies these requirements must be regarded as a true theory of species; while any which does not, is, so far, defective, and must be regarded only as a hypothesis whose value is greater or less, according to its approximation to this standard.

It is Mr. Darwin's peculiar merit to have apprehended these logical necessities, and to have endeavoured to comply with them. The Pigeons called Pouters, Tumblers, Fantails, &c., which the audience had an opportunity of examining, are in his view, the result of so many long-continued experiments on the manufacture of species; and he considers that causes essentially similar to those which have given rise to these birds are operative in nature now, and have in past times been the agents in producing all the species we know. If neither of these positions can be upset, Mr. Darwin's must be regarded as a true theory of species, as well based as any other physical theory: they require, therefore, the most careful and searching criticism.

After pointing out the remarkable differences in structure and habits between the Carrier, Pouter, Fantail, Tumbler, and the wild *Columba livia*, the speaker expressed his entire agreement with Mr. Darwin's conclusion, that all the former domesticated breeds had arisen from the last-named wild stock; and on the following grounds—1. That all interbreed freely with one another. 2. That none of the domesticated breeds presents the slightest approximation to any wild species but *C. livia*, whose characteristic markings are at times exhibited by all. 3. That the known habits of the Indian variety of the Rock Pigeon (*C. intermedia*) render its domestication easily intelligible. 4. That existing varieties connect the extremest modifications of the domestic breeds by insensible links with *C. livia*. 5. That there is historical evidence of the divergence of existing breeds, *e.g.* the Tumbler, from forms less unlike *C. livia*.

The speaker then analyzed the process of selection by which the domesticated breeds had been produced from the Wild Rock Pigeon; and he showed its possibility to depend upon two laws which hold good for all species, viz., 1. That every species tends to vary. 2. That variations are capable of hereditary transmission. The second law is well understood; but the speaker adverted to the miscomprehension which appears to prevail regarding the first, and showed that the variation of a species is by no means an adaptation to conditions in the sense in which that phrase is commonly used. Pigeon-fanciers, in fact, subject their pigeons to a complete uniformity of conditions; but while the similarly used feet, legs, skull, sacral vertebræ, tail feathers, oil gland and crop undergo the most extraordinary modifications; on the other hand, the wings, whose use is hardly ever permitted to the choice breeds, have hitherto shown no sign of diminution. Man has not as yet been able to determine a variation; he only favours those which

arise spontaneously, *i.e.* are determined by unknown conditions.

It must be admitted that, by selection, a species may be made to give rise experimentally to excessively different modifications; and the next question is, Do causes adequate to exert selection exist in nature? On this point, the speaker referred his audience to Mr. Darwin's chapter on the struggle for existence, as affording ample satisfactory proof that such adequate natural causes do exist.

There can be no question that just as man cherishes the varieties he wishes to preserve, and destroys those he does not care about; so nature (even if we consider the physical world as a mere mechanism) must tend to cherish those varieties which are better fitted to work harmoniously with the conditions she offers, and to destroy the rest.

There seems to be no doubt then, that modifications equivalent in extent to the four breeds of pigeons, might be developed from a species by natural causes; and therefore, if it can be shown that these breeds have all the characters which are ever found in species, Mr. Darwin's case would be complete. However, there is as yet no *proof* that, by selection, modifications having the physiological character of species (*i.e.* whose offspring are incapable of propagation, *inter se*) have ever been produced from a common stock.

No doubt the numerous indirect arguments brought forward by Mr. Darwin to weaken the force of this objection are of great weight; no doubt it cannot be proved that all species give rise to hybrids infertile, *inter se*; no doubt (so far as the speaker's private conviction went), a well conducted series of experiments very probably would yield us derivatives from a common stock, whose offspring should be infertile, *inter se*: but we must deal with facts as they stand; and at present it must be admitted that Mr. Darwin's theory does not account for all the phenomena exhibited by species; and so far, falls short of being a satisfactory theory.

Nevertheless the speaker expressed his sense of the extremely high value to be attached to Mr. Darwin's hypothesis; and, avowing his own conviction that the following it out must ultimately lead us to the detection of the laws which have governed the origin of species, he concluded his discourse in the following words, which he wishes to be added in full to the very brief preceding account of his view of Mr. Darwin's argument:—

"I have endeavoured to lay before you what, as I fancy, are the turning points of a great controversy; to render obvious the mode in which the vast problem of the origin of species must be dealt with; and so far as purely scientific considerations go, I have no-

thing more to say. But let me beg you still to listen to a last word respecting the unscientific objections which I constantly hear brought forward, on the part of the general public, against such doctrines as those we have been discussing. For this is a matter upon which it is of the utmost importance that men of science and the public should come to an understanding. I have heard it said, that it is presumptuous for us to attempt to inquire into such matters as these; that they are problems beyond the reach of the human understanding. Do you remember what was the reply of the old philosopher to those who demonstrated to him so clearly the impossibility of motion? 'Solvitur ambulando,' said he, and got up and walked. And so I doubt not that one of these days either Mr. Darwin's hypothesis, or some other, will get up and walk, and that vigorously; and so save us the trouble of any further discussion of this objection.

"Another, and unfortunately a large class of persons take fright at the logical consequences of such a doctrine as that put forth by Mr. Darwin. If all species have arisen in this way, say they—Man himself must have done so; and he and all the animated world must have had a common origin. Most assuredly. No question of it.

"But I would ask, does this logical necessity add one single difficulty of importance to those which already confront us on all sides whenever we contemplate our relations to the surrounding universe? I think not. Let man's mistaken vanity, his foolish contempt for the material world, impel him to struggle as he will, he strives in vain to break through the ties which hold him to matter and the lower forms of life.

"In the face of the demonstrable facts, that the anatomical difference between man and the highest of the *Quadrumana* is less than the difference between the extreme types of the Quadrumanous order; that, in the course of his development, man passes through stages which correspond to, though they are not identical with, those of all the lower animals; that each of us was once a minute and unintelligent particle of yolk-like substance; that our highest faculties are dependent for their exercise upon the presence of a few cubic inches more or less of a certain gas in one's blood; in the face of these tremendous and mysterious facts, I say, what matters it whether a new link is or is not added to the mighty chain which indissolubly binds us to the rest of the universe? Of what part of the glorious fabric of the world has man a right to be ashamed—that he is so desirous to disconnect himself from it? But I would rather reply to this strange objection by suggesting another line of thought.

I would rather point out that perhaps the very noblest use of science as a discipline is, that now and then she brings us face to face with difficulties like these. Laden with our idols, we follow her blithely—till a parting in the roads appears, and she turns, and with a stern face asks us whether we are men enough to cast them aside, and follow her up the steep? Men of science are such by virtue of having answered her with a hearty and unreserved, Yea; by virtue of having made their election to follow science whithersoever she leads, and whatsoever lions be in the path. Their duty is clear enough.

"And, in my apprehension, that of the public is not doubtful. I have said that the man of science is the sworn interpreter of nature in the high court of reason. But of what avail is his honest speech, if ignorance is the assessor of the judge, and prejudice foreman of the jury? I hardly know of a great physical truth, whose universal reception has not been preceded by an epoch in which most estimable persons have maintained that the phenomena investigated were directly dependent on the Divine Will, and that the attempt to investigate them was not only futile, but blasphemous. And there is a wonderful tenacity of life about this sort of opposition to physical science. Crushed and maimed in every battle, it yet seems never to be slain; and after a hundred defeats it is at this day as rampant, though happily not so mischievous, as in the time of Galileo.

"But to those whose life is spent, to use Newton's noble words, in picking up here a pebble and there a pebble on the shores of the great ocean of truth—who watch, day by day, the slow but sure advance of that mighty tide, bearing on its bosom the thousand treasures wherewith man ennobles and beautifies his life—it would be laughable, if it were not so sad, to see the little Canutes of the hour enthroned in solemn state, bidding that great wave to stay, and threatening to check its beneficent progress. The wave rises and they fly; but unlike the brave old Dane, they learn no lesson of humility: the throne is pitched at what seems a safe distance, and the folly is repeated.

"Surely, it is the duty of the public to discourage everything of this kind, to discredit these foolish meddlers who think they do the Almighty a service by preventing a thorough study of his works.

"The Origin of Species is not the first, and it will not be the last, of the great questions born of science, which will demand settlement from this generation. The general mind is seething strangely, and to those who watch the signs of the times, it seems plain that this nineteenth century will see revolutions of thought and practice as

great as those which the sixteenth witnessed. Through what trials and sore contests the civilized world will have to pass in the course of this new reformation, who can tell?

"But I verily believe that come what will, the part which England may play in the battle is a grand and a noble one. She may prove to the world, that for one people, at any rate, despotism and demagoguy are not the necessary alternatives of government; that freedom and order are not incompatible; that reverence is the handmaid of knowledge; that free discussion is the life of truth, and of true unity in a nation.

"Will England play this part? That depends upon how you, the public, deal with science. Cherish her, venerate her, follow her methods faithfully and implicitly in their application to all branches of human thought; and the future of this people will be greater than the past.

"Listen to those who would silence and crush her, and I fear our children will see the glory of England vanishing like Arthur in the mist; they will cry too late the woful cry of Guinever:

> 'It was my duty to have loved the highest;
> It surely was my profit, had I known;
> It would have been my pleasure had I seen.'"

[T. H. H.]

ROYAL INSTITUTION NOTES

Sir Harold Spencer Jones (1890-1960)

A MEMORIAL service for Sir Harold Spencer Jones, K.B.E., Sc.D., F.R.S., was held on 6th December, 1960, at St. James's, Piccadilly. The Rev. J. S. Brewis officiated and the following address was given by **Lord Brabazon of Tara,** P.C., G.B.E., M.C., President of the Royal Institution.

We are here this morning collectively to pay our last respects to Sir Harold Spencer Jones, but his memory will remain long with each individual that knew him. By all standards he was a great man.

When young at Cambridge he was pre-eminent at mathematics; he elected to turn his talents to astronomy. Wise was his choice. Right well did he ornament that profession. His work at the Cape was distinguished, early in 1923 he became there His Majesty's Astronomer at the Royal Observatory. In 1933 he became Astronomer Royal. A splendid title that almost suggests that at Her Majesty's pleasure he controlled the heavens.

There was thrust upon him the duty of moving the Observatory from Greenwich to Herstmonceux—an exacting task which he saw through with remarkable efficiency. However, it is not for me to recite a catalogue of his astronomical triumphs, but they were very real.

On retirement this great man, though still immersed in work, assented to become Secretary of the Royal Institution. He meant a great deal to us.

But this is not the whole story, what was this man like as a human being? I wonder if by being an astronomer you acquire a rather detached and perhaps a truer valuation of the fever of life on this planet, as you contemplate the macroscopic world and watch the cosmos rolling on on its tremendous, majestic way. Was it this that gave to Sir Harold that simplicity and humility that was in him such an endearing and attractive human appeal? If it were, surely we should all study astronomy to get our values right.

To me he was a man never in a hurry; he looked at you with

sphinx-like calm the while you knew he was wisely appraising the situation and arguments you were putting forward, and seeing the main issue. A man of few words, he made up his mind what was right and quickly got on with the task.

He never courted friendship, but it was freely given to him, for he was of all men one you knew you could trust. I hope I have not given the impression that he was without a sense of fun and humour. His deep laugh was singularly satisfying.

It was the same in his family life where he was happy and blessed. I know somewhere we pray against death; but is there not something rather wonderful in this man returning home after attending some duty function and in the recounting of it to his wife, his life-long partner of some forty-two years, suddenly stopping in a sentence, and all was over. I know the shock to those that loved him, but are we not a little selfish in preferring an illness with all the suffering entailed, in order that the shock to his friends might be less sudden.

He was a man, who at all times, was ready to meet his Maker. He has gone from us, and all I can say in conclusion is this. If the almost universal instinct of man is right, that beyond what we call death there be another life in perhaps other dimensions, about which with our finite knowledge we little inderstand, where the great and the good are treasured; then if humility in great accomplishments, purity of purpose, honesty in all things, and a nature that inspired love and peace count for righteousness; then high up there in that new life, amongst the most welcome, will be found the honoured soul of dear Harold Spencer Jones.

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Members of the Royal Institution support by their subscriptions an institution devoted to the prosecution of scientific research and to the diffusion of science and of useful knowledge. Its dual purpose of research and exposition is served by the scientific work carried on in its laboratories and by its Friday Evening Discourses and Lectures on science, literature and the arts.

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